PRINCIPLES OF MODERN BIOLOGY

PRINCIPLES OF

Modern Biology

BY DOUGLAS MARSLAND

New York University

A Complete Reconstruction and Modernization of

CHARLES R. PLUNKETT'S

Elements of Modern Biology



NEW YORK: HENRY HOLT AND COMPANY

November, 1946

PRINTED IN THE UNITED STATES OF AMERICA

CONTENTS

Part I: THE CELL

Part II: MULTICELLULAR PLANTS

Part III: MULTICELLULAR ANIMALS, ESPECIALLY MAN

PREFACE

THE PRESENTATION of biology as a science, i.e., as "a consistent integrated body of knowledge and theory aiming not merely to describe but to explain the phenomena with which it deals"—was the professed and central theme of Charles R. Plunkett's textbooks; and this has continued to be an ideal of the present work. But, in addition, the main objective of this reconstruction and modernization has been to bring the principles of biology definitely within the range of comprehension and interest of college students—without sacrificing scientific standards by over-simplification, or by omitting material because of its complexity.

Abstract biological principles, regardless of how clearly they are stated, fail to engage a student's active interest unless they are related to common experience, or to experiments and observations which are fully and clearly explained. This precept required not only a very complete rewriting of the text, but also the addition of many new illustrations which fully exemplify every discussion. Nevertheless, the basic integration of the biological principles has been zealously retained, and this represents a most important heritage from the initial work.

A main departure is that the reorganization introduces the principles of nutrition, responsiveness, and reproduction in a very early section, i.e., in Part I, The Cell. Thus from the outset the student can see the organism as a whole, and can apply his knowledge without delay to such forms as are studied in the earlier parts of the laboratory work. Moreover, by returning to the basic principles of nutrition, responsiveness, and reproduction in two subsequent sections (Part II, Multicellular Plants, and Part III, Multicellular Animals) the new organization reinforces the learning of these very fundamental concepts.

In the new text, attention is focused more sharply upon man—his bodily functions, his practical problems and his biological background. This may narrow the perspective somewhat, but long experience has proved that it arouses a greater interest and more effectively motivates the learning of the general principles.

Many have urged that the morphological content of the text be fortified, and this has been done—while still preserving the intrinsic character of the original work. In all sections, an adequate morphological basis has been provided for the physiological, developmental, and taxonomic principles which are discussed. But the detailed morphology of plant and animal types —which properly should be acquired by a direct observation of the specimens—is purposely left for full development in the laboratory.

Biology has made many advances since the Plunkett books were published and a good deal of this new material has been added—especially on the viruses, enzymes, hormones, and vitamins—and on such topics as photosynthesis and cellular metabolism. However, the task of "modernizing" a comprehensive text in general biology is prodigious, and one can only hope that the most important recent advances have been included.

My associates at the Washington Square College of Arts and Sciences have been most generous, not only in combing the manuscript for errors and ambiguities, but also in helping to develop a large part of the content of the text. In a very real sense, the book originates from the lectures of our general biology course, and during recent years many members of the Biology Department have contributed to these lectures. Accordingly, I take pleasure in acknowledging great indebtedness to Drs. Harry A. Charipper, Albert S. Gordon, Morris H. Harnly, Ruth B. Howland, Alexander Sandow, and Malvina Schweizer. Also, I want to express my gratitude to Drs. S. C. Brooks, R. H. Cheney, R. Gaunt, O. Glaser, M. Kopac, S. F. Light, F. Pitelka and H. B. Steinbach—for many helpful suggestions and criticisms; and to Drs. R. W. Gerard, E. B.

Harvey and M. S. MacDougall—for contributing essential illustrations; and to Dagmar Carpenter and James Christiansen—for their work on the new line drawings.

Finally I wish to acknowledge a very special indebtedness to the late Henry J. Fry, who patterned the General Biology Course at Washington Square College during the formative years, and who directed my early teaching at the college. And last but not least, I gratefully dedicate my share of the work to Alice Marsland, who helped in so many ways, both tangible and intangible.

D. M.

New York University
Washington Square College
of Arts and Sciences
April, 1945

PART I

THE CELL

CHAPTER I

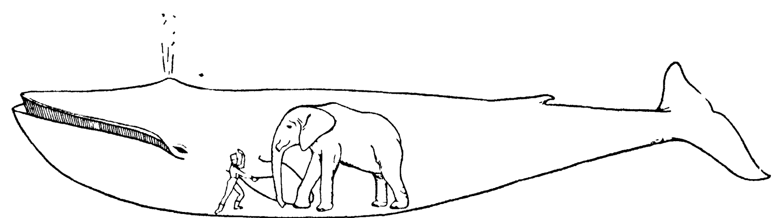
LIFE AND PROTOPLASM

MORE than a million and a quarter distinct species of plants and animals are recognized in the world at large, and quite a number of newly discovered species are reported every year. Different organisms have evolved a special fitness to live in almost every part of the environment—in the ocean, on land and in the air—under a wide variety of conditions. Certain species thrive on dry rocks and in stagnant swamps; in hot springs and in polar ices; where oxygen is abundant, and even where oxygen is lacking entirely.

Some organisms appear to be very simple—like microscopic droplets of clear liquid. But other creatures, like man, possess an obviously complicated structure. Gigantic living things, like whales or redwood trees, stand in dramatic contrast to the puniest bacterium, which looks like the smallest speck, even under the best magnification of the microscope. In short, a very rich diversity of living creatures has been evolved upon our earth, and man is challenged to reach an understanding of their nature (Fig. 1).

Distinctive Activities of Living Bodies. Since *biology* is the group of sciences which *deals with life* in all its forms and in all its activities, it is necessary to distinguish as clearly as possible between living and non-living bodies. Such a distinction is not usually difficult, because living bodies are apt to display several unmistakable signs of life. All typical organisms are *responsive,* i.e., all living things react to stimulation—by

chemical agents such as food, or by physical agents such as light. Likewise, all living things sustain themselves by some kind of *nutrition.* Each takes in food from which to derive matter for growth and energy for movement. And above all, each living thing displays a capacity for *reproduction,* perpetuating itself from generation to generation. In fact, these three activities—*responsiveness, nutrition,* and *reproduction*—are uniquely combined in living bodies, and can be taken as the main criteria of the *living state* (Fig. 2).



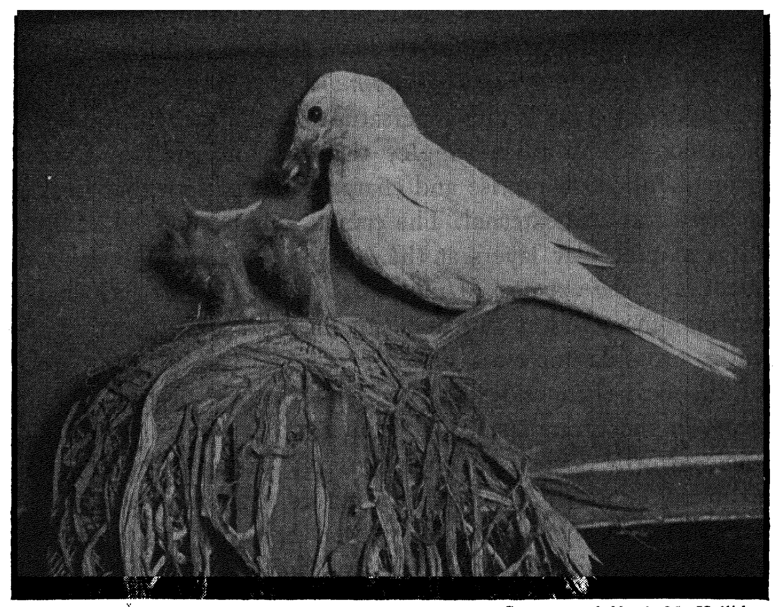
Redrawn (modified) from Lull, *Organic Evolution,* The Macmillan Company

FIG. 1.—The size of organisms varies greatly. This whale (a sulfur bottom whale) weighs over 2,000,000 pounds, and the elephant weighs 20,000 pounds. But it takes more than a trillion tuberculosis bacilli to make one pound.

Responsiveness of Non-living Bodies. One must conclude, however, that the dividing line between the living and non-living is not a very sharp one, because a number of non-living systems can be found which simulate some aspects of living behavior. All bodies, non-living as well as living, are in some degree responsive; and some non-living things display activities analogous to nutrition and growth. Water, or any other form of matter, continually alters its behavior in response to changes in temperature, pressure, light and other factors of the environment. Water expands or contracts according to the temperature; it boils at one temperature and freezes at another. These are relatively simple reactions, hardly to be compared to the complex responses of a thinking man, or of a sprouting seed. But there are non-living systems which are highly reactive—as for example, a loaded pistol responding to a touch on the trigger, or an automobile responding to pressure on the accelerator.

Nutrition in Non-living Systems. Non-living bodies may also display nutrition, although generally the nutrition of liv-

ing bodies is considerably more complex. Within the living body food always contributes both *energy*—the energy which activates the vital system—and *matter*, to form new components in the living structure. In other words, food in the living body can serve not only as a *fuel*, but also as raw material for chemical syntheses which provide for *maintenance*, and lead to *growth*.



Courtesy of Hugh M. Halliday

FIG. 2.—Responsiveness, nutrition and reproduction are characteristic of living things. Incidentally, this adult female robin is a fairly rare white (albino) specimen.

Many inanimate bodies utilize fuels, but few, if any, can grow or even maintain their existing structure. An automobile duplicates almost all of the destructive phases of animate nutrition. It takes in fuel (food); it distributes the fuel to the carburetor; it sucks in (breathes) oxygen through the carburetor which sends the fuel-oxygen mixture to the cylinders; it chemically decomposes (oxidizes) the fuel and utilizes the energy which is liberated for the development of mechanical power. Furthermore, the automobile must eliminate (excrete) the end-products

(waste-products) of its chemical activities. But here the analogy stops. The automobile cannot grow. It cannot even replace the small structural losses which inevitably result from wear and tear. All of the constructive phases of nutrition, by which new substances are chemically synthesized and utilized for maintenance and growth in every living body, are absent in all inanimate systems.

Growth and Reproduction: The Most Unique Activities of Living Systems. Biologists have tried to find a parallel to the characteristic *growth phenomena* of living bodies in the "growth" of crystals in a supersaturated solution. But this phenomenon seems much simpler than organic growth. Crystal growth follows a precise and characteristic pattern, but is altogether local and external. The crystal enlarges by the addition of new molecular layers at the *surface* only, and the enlargement is at the expense of molecules which exist as such in the surrounding solution. Organic growth, in contrast, pervades the entire protoplasmic mass, and depends upon an elaborate series of chemical changes leading to the formation of new components in the protoplasm. Or, from another point of view, organic growth depends upon a precisely patterned aggregation of many kinds of molecules, whereas crystals grow by the assemblage of one, or at most, two or three kinds of molecules.

The most unique characteristic of living bodies is the capacity for *reproduction;* and here it is hard to find any convincing inanimate examples. From the humblest bacterium to the mightiest mammal, each living species must maintain an unbroken line of descent, if it is to avoid extinction. The processes of reproduction are extremely complex and delicate even in the simpler forms of life. The formation of a new body, which is almost an exact replica of the old, presupposes the existence of a delicate mechanism which can sort out the important components of each living system and pass these on to each ensuing generation.

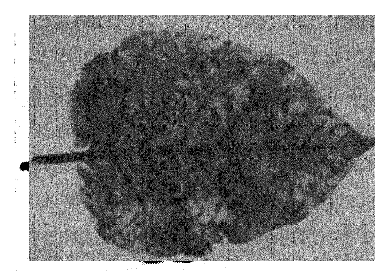
Certain inanimate bodies, namely crystals, may show an extremely simple form of "reproduction." Occasionally, while a small crystal is in the process of "growing," it will fragment

spontaneously and each of the fragments will become the center around which a perfect new crystal will form. However, with the possible exception of the multiplication of the filterable viruses (see below) such a "reproductive process" is incomparably simpler than all cases of animate reproduction.

Filterable Viruses. Possibly our concept of the living state will require fundamental revision in the light of further knowledge. Ever since the dawn of biological curiosity, when the early cavemen first began to draw pictures of the plants and animals which shared their environment, man has continued to discover and record new forms of life. Before the seventeenth century, when the microscope first revealed a whole new world of living minutiae, generation after generation of protozoa, bacteria and other microscopic forms had lived and died without the blessing of man's cognizance. The biologists of that day were slow to admit these new organisms into the fraternity of life, and many years of research and controversy followed before the micro-organisms were recognized generally. Today, it is the filterable viruses which seem to lie at the boundary line between the living and the non-living. If biologists finally conclude that the viruses are alive, then it will have to be admitted that a continuous intergradation exists between non-living and living forms of matter.

Little or nothing was known about the viruses until 1918, when d'Herelle discovered the first bacteriophage. In the previous century, Pasteur, Koch, Reed and others had demonstrated that many diseases in plants and animals are caused by parasites—such as bacteria and protozoa—which invade the tissues of other plants or animals. But in the present century it soon became apparent that other diseases must involve infective bodies much smaller and simpler than any known micro-organism. Now, in fact, a fairly large number of virus diseases are recognized. Among human diseases, smallpox, infantile paralysis, influenza and measles are known to be virus diseases, and the bacteriophages and the mosaic infections are viruses which produce diseases among the plants.

One unique fact about a virus is the extreme smallness and simplicity of the discrete units which compose its mass. If one takes a fluid containing bacteria and forces this fluid through a porcelain filter (ultra-filter), the filtrate obtained is found to be sterile, i.e., entirely free of bacteria. Apparently the pores of such a filter are so small that they prevent the bacteria from passing through. If, however, one ultrafilters a fluid containing the particles of a virus—such as the juice which can be squeezed from a tobacco plant infected with the tobacco mosaic disease (Fig. 3), or the fluid derived from the brain of a monkey infected with infantile paralysis—the virus appears in the filtrate, quite undiminished in quantity.



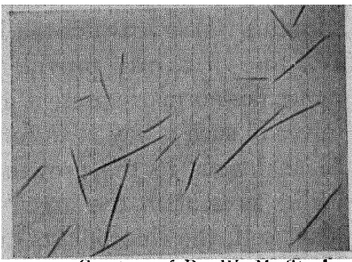
Courtesy of Dr. W. M. Stanley

FIG. 3.—A tobacco leaf infected with the mosaic virus.

Growth and Reproduction of Viruses. Another important characteristic of the viruses is that each possesses, under the proper conditions, an unlimited capacity for growth and reproduction. Take, for example, the virus which gives rise to infantile paralysis in man and certain monkeys. This virus can be transmitted from monkey to monkey in endless succession, without any sign of limit. The smallest quantity of fluid from the brain of a diseased animal, implanted into the brain of a healthy monkey, leads in due time to the paralytic symptoms in the inoculated animal. During the *incubation period*, the original minute quantity of virus increases to a tremendous extent. The virus spreads throughout all parts of the nervous system. Finally, every small fraction of the brain of the newly paralyzed animal contains as much of the virus as was originally introduced into the one localized site of injection.

Isolation of a Virus. In 1935 one of the viruses, the *tobacco mosaic virus*, was isolated and identified. To separate the virus from the many inactive components present in the total juice from an infected tobacco plant, two stages of centrifuging can be

employed. First, an ordinary low-speed centrifuge is used to remove all larger particles, such as bacteria and other microscopically visible bodies. This leaves a perfectly clear supernatant fluid which retains its infective potency in full strength. The second centrifuge is of the high speed type, called an *ultra-centrifuge.* Such a machine can develop centrifugal forces of about half a million times gravity. When a solution is subjected to this force, the larger molecular components tend to be thrown out of solution, and tend to accumulate at the bottom of the test tube. In the present case, the sedimented material proved to be the virus in a practically pure condition. In other words, this sample of virus was practically free from contamination by any inactive materials. After further simple chemical treatment, the virus was obtained in the form of crystals (Fig. 4) which displayed a high degree of purity.



Courtesy of Dr. W. M. Stanley

FIG. 4.—Crystals of tobacco mosaic virus (× 675).

Unit Structure of a Virus. Analysis of the tobacco mosaic virus, and of several other viruses which meanwhile have been isolated, proved that the *smallest discrete particles of the virus are single molecules of a specific protein substance.* All protein molecules are large and complex, compared to simple molecules such as water or sugar. But virus molecules are giants even among proteins. The simplest bacterium is composed of a great number of molecules, among which many large proteins are represented.

Even the largest molecule is not large enough to reflect a definite pattern of light, and therefore no individual virus particle has ever been seen with an ordinary microscope. However, the *electron microscope* is being used to determine the molecular structure of viruses, and this structure appears to be scarcely more complex than that of certain other protein substances. Consequently if it is ever proved that the viruses are alive, it

will then have to be admitted that the simplest living things are scarcely distinguishable from a number of non-living substances.

Are Viruses Alive? The crux of the problem as to whether or not the viruses are alive, lies in the fact that no virus has ever displayed growth except in association with some well-recognized form of life. The virus grows and reproduces only in the presence of some kind of living tissue—and this may not be independent growth. Possibly the virus serves merely as a stimulus which activates the living cells to produce more virus; i.e., the virus may provide a pattern which activates certain molecules normally present in the living cells to assemble themselves in such a way as to form more virus protein. This would be analogous to the growth of chloroplasts, the small green bodies present in the green tissues of all typical plants. In a plant cell, the chloroplasts can multiply without limit, but if a chloroplast is isolated from the living cell, it soon disintegrates. In other words, chloroplasts are enabled by the living system to produce more chloroplasts, but by themselves chloroplasts have no intrinsic capacity for growth or multiplication.

Investigators have attempted to cultivate many different viruses, but none has succeeded in obtaining spontaneous multiplication in media from which all admittedly living units were excluded. Until such growth is demonstrated, the living nature of viruses must remain in doubt. Meanwhile it seems valid to regard the viruses as transitional between living and non-living matter.

The Progress of Science. A *science* is a systematically organized body of knowledge, based upon precise unbiased observation, and integrated by logical reasoning. To the fullest possible extent, scientific knowledge is checked and counterchecked by carefully planned and strictly controlled experiments.

Without special training in scientific research, man has always been quite helpless in trying to understand the nature of his universe. In very early times man depended upon superstition to cover his ignorance of natural events; and this led to the creation of many gods: of the wind, the sun, the harvest, and

so forth. But even at the dawn of civilization, some capacity for accurate observation was gradually developing, as can be seen in the records of animal and plant life which the cave-dwellers painted by torchlight on the walls of their ancient homes (Fig. 5).

Early civilized men, especially the Egyptians, Greeks, and Romans, began to use direct observation rather than superstitious tradition, as the basis of their thinking. In fact the ancients began to test their conclusions by experiment; and many roots of our scientific knowledge can be traced back into the classical period.



Courtesy of the American Museum of Natural History, New York

FIG. 5.—Scientific observation began in prehistoric times. Cro-Magnon artists in the Cavern of Font de Gaume.

But the scientific attitude did not survive. After the decline of the Romans, superstition prevailed again for almost fourteen centuries. The scant scientific knowledge which survived the dark ages was "second hand"—passed on from generation to generation, chiefly by the medieval monks.

During the Renaissance, much of the ancient learning was revived and science began to gain a new momentum. Gradually the scientific method came into its own. Especially during the past seventy-five years—well within the memory of our fathers and grandfathers—research laboratories have developed in every important university, in every industry, and in every part

of the world. This new group of workers has been carefully trained in the scientific method, and has widely extended the frontiers of natural science. Consequently the present-day student of biology, chemistry, physics, or other science, begins work with a double heritage. He receives not only a large fund of knowledge, tested by the scientists of every nation, but also a most useful tool—the fully developed *method of science.*

The Scientific Method. The scientific method proceeds precisely, according to a well-defined plan. Alternately it utilizes both the inductive and deductive types of reasoning. The plan involves *four steps*—and the same four steps are continually repeated, as new ground is being gained and tested.

1. *Observation.* The primary basis of all scientific thinking is observation—direct, precise and unbiased by any preconception as to the significance of the observed data. The current hypothesis or theory may indicate the field in which new more exact observations are needed. But the scientist must never be guilty of weighting the data in favor of his preconceptions.

2. *Interpretation.* The second step in the research technique is to formulate a logical explanation of the observed data. This involves setting up a tentative *hypothesis.* The hypothesis is usually broader than the data from which it is *induced,* and consequently the hypothesis must remain tentative until further observation either confirms or denies its validity.

3. *Prediction.* This third step of the scientific method requires that predictions be *deduced* from the working hypothesis. On the basis of such predictions new experiments are suggested for testing the hypothesis in question. If the predictions are verified by the experiments, the hypothesis is strengthened; if not, the hypothesis must be modified, or discarded.

4. *Experimentation.* Each experiment is calculated to test the predictions which are deduced from a particular hypothesis. The experiment is so designed that it yields a single answer regarding the prediction in question. Accordingly each experiment must be accompanied by a *control* in which all factors, except the one being investigated, are duplicated in the *strictest possible* fashion.

Experimental Control. Assume, for example, that it is necessary to test a simple hypothesis: that the loss of consciousness experienced by an aviator at high altitude depends upon a scarcity of oxygen. To prove this, it is necessary to subject the aviator to an experiment which rules out all other possibilities. At high altitude not only is the oxygen scarce, but also the total atmospheric pressure and the temperature are greatly reduced. Therefore, to decide the issue, it is necessary to set up a control experiment, utilizing a chamber in which both the temperature and the composition of the atmospheric gases can be regulated. In the control experiment, the temperature and total air pressure would have to be lowered to the level indicated by the altitude in question, while at the same time the available oxygen was maintained at the normal value. Under these conditions consciousness would not be lost. Consequently it could be concluded that the hypothesis was sound, and that unconsciousness does in fact depend upon a *scarcity of oxygen.*

Hypothesis, Theory and Principle. The scientific method may be illustrated more completely, by considering an early hypothesis—as to the nature of *combustion,* or burning. This *phlogiston hypothesis* held favor prior to the discovery of oxygen by Lavoisier in 1776.

The phlogiston hypothesis held that combustible material, such as wood, contains an unknown gaseous substance, called *phlogiston,* which begins to escape as soon as a material is heated sufficiently to begin burning. The hypothesis was based upon certain observations: something (the flame) appears to escape from the burning body, and the ash, or remnant of combustion, usually has a lesser weight than the unburned material. But one deducible prediction of this hypothesis is that every material must be lighter after burning; and this prediction cannot be verified by all experiments. Some materials, such as magnesium, i.e., the foil which burns with glaring speed in a photographic flashlight bulb, shows an increase of weight after combustion. The ash, magnesium oxide (MgO), is significantly heavier than the unburned magnesium (Mg). In view of such exceptions, it became necessary to discard the phlogiston hypoth-

esis. Then, with the discovery of oxygen, a new hypothesis—the *oxidation hypothesis*—was formulated. This hypothesis was tested by countless experiments which extended through many years. Gradually the oxidation hypothesis received sufficient confirmation to be called a *theory*, and finally the *oxidation principle* has taken its place as one of the established and fundamental *laws*, or *principles*, of chemical science.

The Biological Sciences. In a broad sense, all phases of science which deal with life and living things lie within the province of biology. However, it is customary to separate the biological sciences into three parts: (1) Sociology (L. *socius* = society, and Gr. *logos* = study), which deals with social behavior, especially in man; (2) Psychology (Gr. *psyche* = mind), which treats of individual behavior, likewise primarily in man; and (3) Biology (Gr. *bios* = life), which embraces all other vital phenomena.

Biology proper is further subdivided in complex fashion, as is shown diagrammatically in Fig. 6. This diagram fails to show many of the more detailed subdivisions: bacteriology, protozoology, etc., which correspond to the various groups in the plant and animal kingdoms (see Appendix I).

Uses of Biology. From a practical viewpoint, the study of biology provides a foundation for many specialized professions. In medicine, or dentistry, for example, every phase of the training—every subject in the medical and dental curricula—is essentially a part of biology. Unless these special trainings are rooted in a sound conception of *general principles*, the practitioner lacks a background for critical judgment, and proceeds by rule of thumb. Likewise in many other fields: in forestry, agriculture and horticulture; in animal and plant breeding; in veterinary medicine and in the work of the fisheries; biology has great value. And in fact, it cannot be said that a knowledge of the general principles of biology lacks tangible value in any field of human endeavor.

Life and Protoplasm. To define life completely is scarcely possible, but the word can be used to designate the sum total of all activities—*responsiveness*, *nutrition*, *reproduction*, etc.—

which are displayed by living bodies generally. Life, according to this usage, simply specifies "what living things do." It does not in any sense *explain* what they do, or *how* they do it.

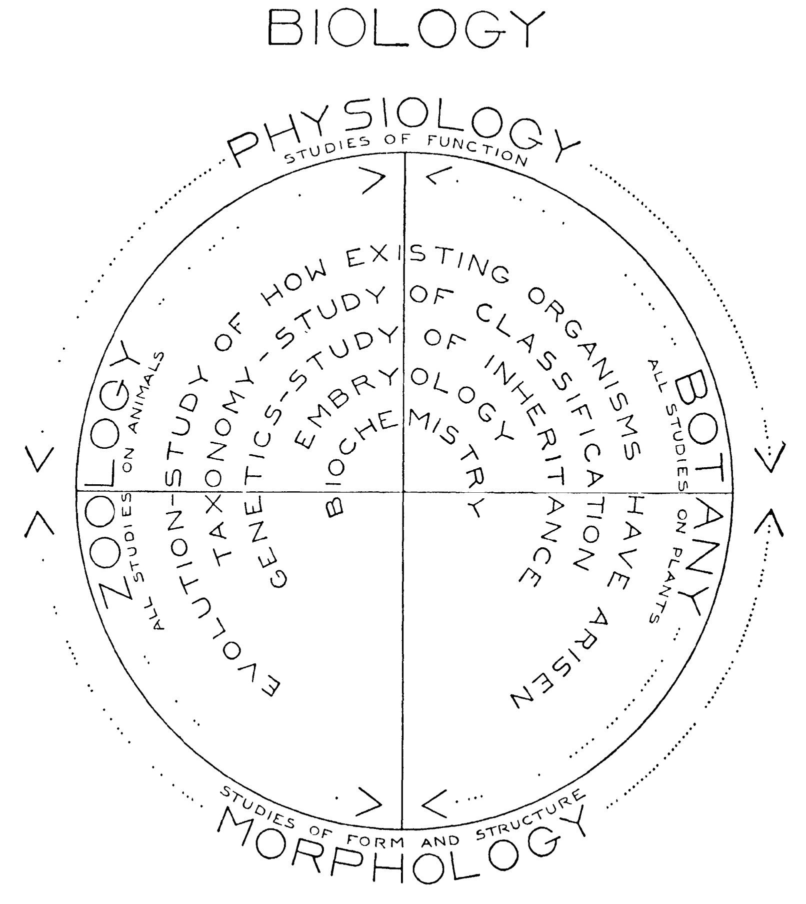


Fig. 6—Main subdivisions of biological science.

Popularly the word "life" is sometimes used in a different sense: to designate a mysterious immaterial "something" which uniquely resides in living bodies, causing their activities. Science, however, has not been able to find the slightest evidence to confirm the existence of anything corresponding to this idea. Nor is such a concept useful. To say that a living body moves,

responds, or grows, "because it is alive" or because "it possesses life" is like saying that a motor runs "because it is motile," or "because it possesses motility." In science such so-called explanations are not admissible. The only scientifically valid kind of explanation consists in finding and describing an actual mechanism, in which the special composition, arrangement and interaction of the component parts logically accounts for the observed activities.

In accordance with this important criterion of science, the aim of biology is to explain life—the activities of living bodies—in terms of the composition and structure of these bodies: what materials are present, how the component materials are uniquely organized in the living body, and how these components interact to generate the activities which are recognized as life. Just as the chemist, or the physicist, probes into the visible and subvisible structure of non-living matter in seeking to understand its behavior, so the biologist, using essentially the same methods, investigates the ultimate structure of living matter.

Protoplasm. The phenomena of life are never found except in association with a particular kind of matter. This *living matter is called protoplasm.* Protoplasm is a colorless, translucent, gelatinous fluid, which composes the living part of every living thing. All other parts of any living body—bone, cartilage, wood, etc.—are produced by the protoplasmic parts. *Protoplasm,* therefore, must be regarded as the *physical basis of life.* In the ultimate composition and structure of protoplasm, the answer to life's unique riddle must be sought.

Protoplasmic Structure. Protoplasm is not a single homogeneous substance, but a mixture of many substances. Some of these substances, such as water and mineral salts, are also abundant in non-living nature. But protoplasm is especially characterized, chemically, by containing a high proportion of very complex substances, the *proteins,* which are found nowhere *in nature* except as components or products of protoplasm. In addition to its complex chemical composition, protoplasm also displays a highly *complex structure.* This is not visible to the naked eye, but is revealed, at least in part, by the microscope.

Under the microscope it can be seen that the protoplasm of practically all living bodies is made up of definite units, called *cells*, and that each cell, being composed of protoplasm, is itself alive. Simpler living things may consist each of a single cell; and larger plants and animals are composed of many cells. Each complete living body, whether composed of one, a few, or many cells, is called an *organism*.

The cell itself displays a delicate internal structure, many details of which can be seen with a good microscope. But beyond the utmost limit of the microscope, protoplasm has a still finer, and probably very complex, *ultramicroscopic structure* which can be revealed only by other methods.

Structure in Relation to Function. Protoplasm is characterized by its activities no less than by its composition and structure. There is no such thing as "dead protoplasm": the structure and the activities of protoplasm are inseparable. When the activities of protoplasm cease, its structure immediately begins to break down, and soon it is no longer truly protoplasm. In other words, protoplasm is an unstable system. It can be maintained only by a continuous expenditure of energy—i.e., by "doing work." This situation is comparable to that of an airplane flying at high altitude. The altitude can be maintained only by a continuous expenditure of energy, derived from the combustion of gasoline in the motor. Protoplasm can be stabilized, to a limited extent under certain circumstances, but never completely. It can be kept from "losing altitude"—i.e., losing its functioning structure—only by a continuous expenditure of energy. This energy comes from the chemical processes which ceaselessly go on in every living cell. Collectively these chemical processes are called *metabolism*. The substances consumed in metabolism come from the outside, in the form of food. The various processes by which food is taken into the organism, distributed to all the cells, chemically transformed and utilized within the cells, and eliminated in the form of waste products, constitute *nutrition*.

Not all the energy which is liberated by metabolism, however, goes merely to maintain the protoplasmic structure. As

in the airplane, much of the energy appears in the form of movement, heat, and to a small extent as electric currents. These various reactions (chemical, electrical, mechanical, etc.) in the cells are modified by many external and internal conditions (heat, light, pressure, electricity, chemical substances, etc.). Hence the *responsiveness* of an organism is shaped by the various conditions of the environment.

Provided the food supply is adequate, metabolism not merely maintains the protoplasm already present, but increases it. One of the most characteristic activities of protoplasm is the production, from the substances taken in as food, of more protoplasm. This phase of metabolism results in *growth*, of the cell, and of the organism. Not only is the amount of protoplasm thus increased by its own activities, but also the number of its organized units is increased: cells produce new cells, and organisms new organisms—which, of course, is *reproduction.*

All forms of activity which we recognize as characteristic of living things, and which constitute what we call life, are simply the characteristic and universal activities of protoplasm. Life, therefore, is the total of protoplasmic activities; and conversely, *protoplasm is living matter.*

Because of the incompleteness of our present knowledge, no one has yet been able to produce protoplasm "artificially." Nonliving matter is continually converted into living matter, by the processes of nutrition in living organisms; and living matter is continually reconverted into lifeless matter by metabolism and by the death of organisms. But so far as we actually know, non-living matter is converted into living matter only in intimate association with existing protoplasm—that is, in living organisms. In this present geological age, living organisms are known to originate only from other living organisms, by the processes of reproduction. It seems logically inevitable that living matter must have originated, in the remote past, from nonliving matter, without the intervention of previously living matter, but we have no adequate evidence as to how, or under what conditions, this occurred.

TEST QUESTIONS

1. Specify the activities which are generally exhibited by living things. To what extent are these activities limited to living things?
2. Explain how the "growth" of a crystal differs from the growth of typical living bodies?
3. Name three viruses and explain how the viruses differ *structurally* from simple living organisms such as bacteria.
4. Why is it necessary to reserve judgment in deciding whether or not the viruses are alive? Explain carefully.
5. Explain why *control experiments* are very important, exemplifying the discussion by a specific example.
6. Differentiate between hypothesis, theory, and principle, using specific examples.
7. Explain why hypotheses are important in scientific research.
8. Give a careful definition for each of the following terms: (a) life; (b) protoplasm; (c) biology; (d) nutrition; (e) responsiveness; (f) reproduction; (g) metabolism; (h) ultramicroscopic structure.
9. What is the basis of the statement that "protoplasm displays an unstable structure"?

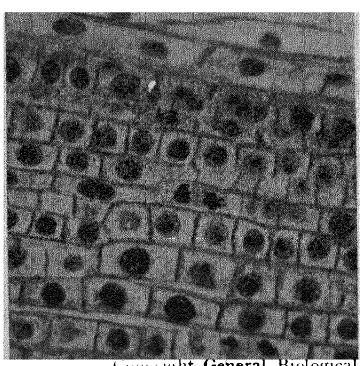
FURTHER READINGS

1. *The Virus: Life's Enemy,* by Kenneth M. Smith; New York, 1940.
2. *The Physical Basis of Life,* by Edmund B. Wilson; New Haven, 1923.

CHAPTER 2

PROTOPLASM, THE CELL, AND THE ORGANISM

PROTOPLASM seldom occurs in large continuous masses, but usually assumes the form of relatively small discrete bodies. Typically each of these unit masses of protoplasm represents a single *cell* (Fig. 7). Until about a hundred and fifty years ago, very little was known about cells; but since that time biologists have recognized that the living part of every living thing is composed of cells—one or a few in simpler organisms, and millions in larger forms like man.



Copyright General Biological Supply House, Chicago

FIG. 7.—Photomicrograph showing typical cells in the root of an onion plant. Note that a nucleus and cytoplasm are visible in most of the cells, although the nuclei are out of focus in a few. Some of the cells are dividing.

The Cell. A typical cell is an organized unit mass of protoplasm, consisting of two distinct regions, the *nucleus* and the *cytoplasm*, and bounded by at least one surface membrane, the *plasma membrane*. The nucleus tends to occupy a central position in the cell, delimited from the surrounding cytoplasm by the *nuclear membrane* (Fig. 8). The nucleus and cytoplasm are both essential parts of the protoplasm, each being complementary to the other. No "cell" can endure, or long continue its vital activities, in the complete absence of either its nucleus, or its cytoplasm.

A few unicellular organisms such as *bacteria,* do not show a distinct separation of the nuclear and cytoplasmic materials (Fig. 9). In such cells the *chromatin*—a material which is found

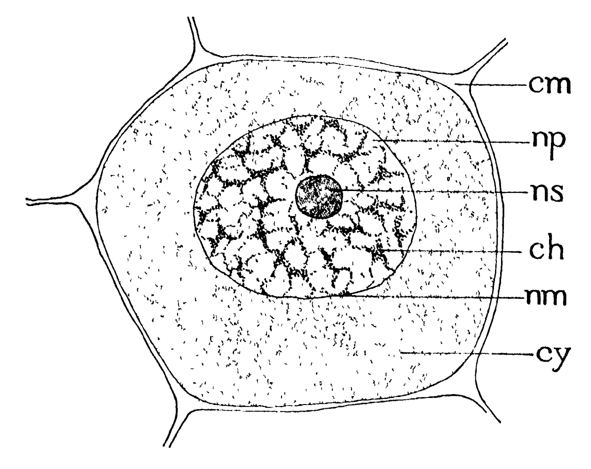


Fig. 8.—A typical animal cell, from the musk-gland of an alligator. ch, chromatin; np, nucleoplasm or nuclear sap; ns, nucleolus, nm, nuclear membrane, cy, cytoplasm; cm, cell membrane.

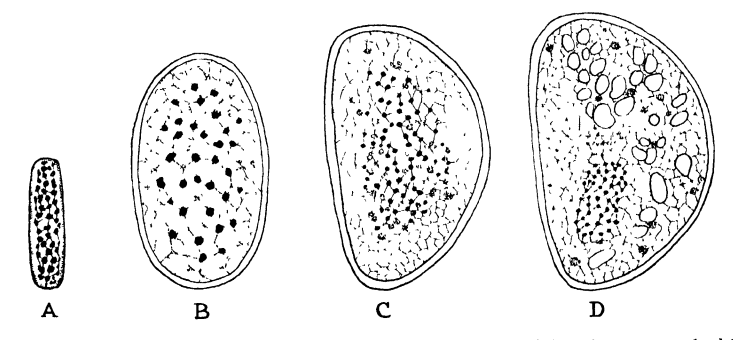


Fig. 9.—Simple organisms with "chromidial" nuclei, the most darkly stained material is chromatin. A, a typical bacterium, with the chromatin distributed throughout the cell. B, C, and D, different species of blue-green algae showing conditions intermediate between the distributed and the definitely delimited types of nuclei. (B, C, and D after Acton.)

only in the nuclei of other cells—is scattered throughout the cytoplasm in the form of numerous fine granules. Another relatively rare condition is displayed by certain primitive *molds,* and a few other organisms. In these cases no limiting mem-

branes are found between the individual "cells"; but rather, several nuclei are enveloped within a common mass of cytoplasm (Fig. 10). Both of these atypical conditions have been designated as "noncellular"; but it seems more logical to regard them as variations of the usual protoplasmic pattern, which differ from the normal only in the lack of limiting membranes

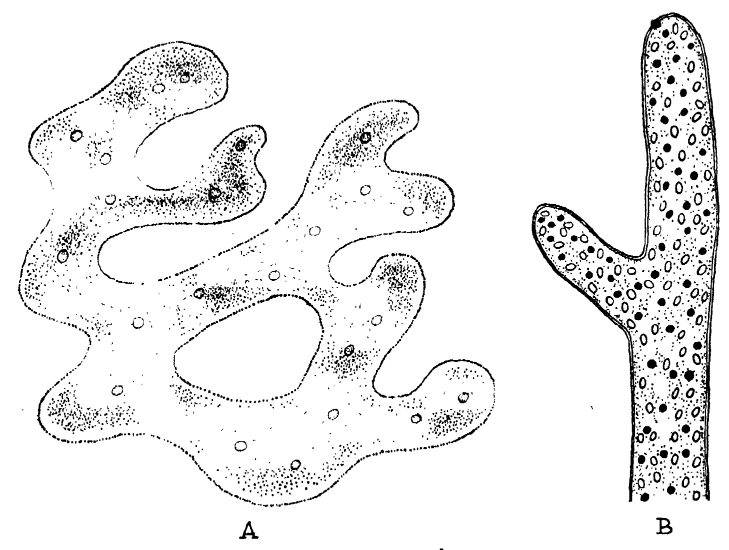


FIG. 10.—A, small part of a slime mold, with many nuclei scattered through the continuous mass of cytoplasm. B, small portion of filament of a green alga, with many nuclei and chloroplasts scattered through the continuous cytoplasm. The nuclei are the very dark bodies.

—between the nucleus and cytoplasm in the first case, and between adjacent cells in the second.

The Size of Cells. A great majority of cells are too small to be seen with the naked eye, which can only resolve an object if the diameter is more than 0.1 millimeter (mm.). However, most cells can be seen plainly with the microscope, which extends the range of vision a thousandfold—down to diameters of about 0.1 micron (μ). Many bacteria—which are probably the smallest cells—lie at the very lowest limit of microscopic visibility (Figs. 11 and 12). At the other extreme, the largest

single cells are the egg cells of birds and fishes. This kind of cell—which popularly is designated as the "yolk of the egg"—may measure more than 3 cm. in diameter, as in the case of the ostrich egg. But such examples are quite rare. Most cells, in both plants and animals, have dimensions between 1 and 100

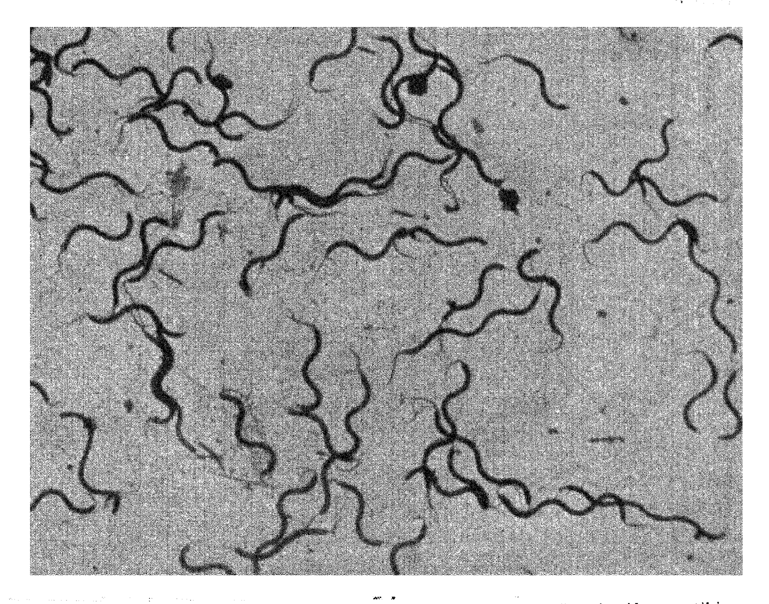


FIG. 11.—Stained bacteria at a magnification of about 10,000 diameters. Note that the nuclear material (chromatin), which takes the stain, is spread evenly throughout the cell.

microns, and thus most cells lie definitely within the range of the compound microscope.

There is a natural limit to the growth of any cell. To support metabolism the cell must be able to obtain an adequate supply of oxygen and other foods, and to give off carbon dioxide and other wastes fast enough to avoid accumulation. These necessary exchanges between the cell and the environment can occur only at the surface of the cell, whereas metabolic activity pervades the entire protoplasmic mass. Consequently, the surface of the cell must be kept adequately large in proportion to the proto-

plasmic volume. But as a cell grows larger, particularly if its shape is compact and rounded, the proportion of surface to volume steadily diminishes. In a sphere, for example, the surface increases merely as the square of the diameter, whereas the volume increases in proportion to the cube of the diameter. Accordingly, when a cell grows larger, it reaches a natural limit

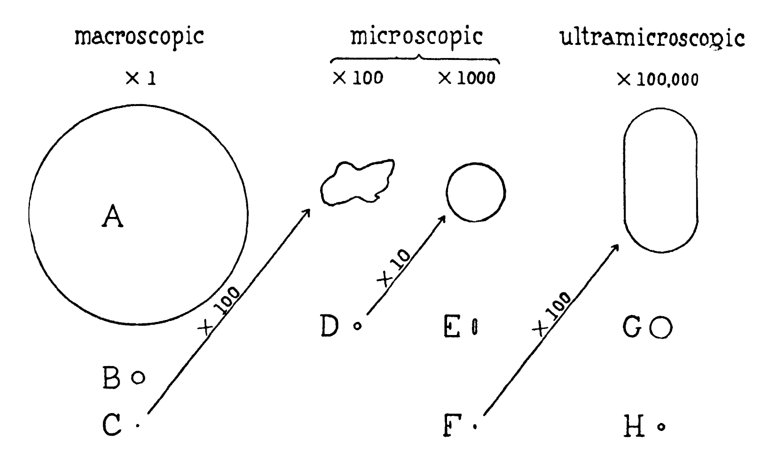


FIG. 12.—Relative sizes of cells: A, egg-cell ("yolk") of hen's egg (3 cm.); B, frog's egg (1.75 mm.); C, Amoeba, a unicellular animal (0.1 mm. = 100μ); D, red blood corpuscle of man (8.5μ); E, typhoid bacillus, an average-sized bacterium (2 × 0.5μ); F, Bacterium pneumosintes, which lies at the extreme limit of microscopic visibility (0.2 × 0.1μ = 200 × 100μ); G, relative size of the filtiable virus which causes the mosaic disease of the tobacco plant (30 mμ); H, relative size of many large molecules (6 mμ).

when its surface area becomes too small in proportion to its volume. This limit varies according to each particular cell-shape, and according to the intensity of metabolism. But when the limit is reached, the cell must either stop growing, or it must divide.

The Form of Cells. Different cells assume a great variety of shapes: spherical or oval; fixed or changeable; flat or elongate; spindle-shaped or lobose; polyhedral or cylindrical; and so forth. But generally speaking the form of each cell bears a distinct relation to its particular function. Nerve cells, for example, are elongate and branched, a form which enables the cells to conduct impulses from one part of the body to another

(Fig. 13); or epithelial cells—which cover the surfaces of the body—take the form of overlapping tiles, as in the skin of many animals, or of variously shaped bricks, as in the lining of man's digestive tract (Fig. 14).

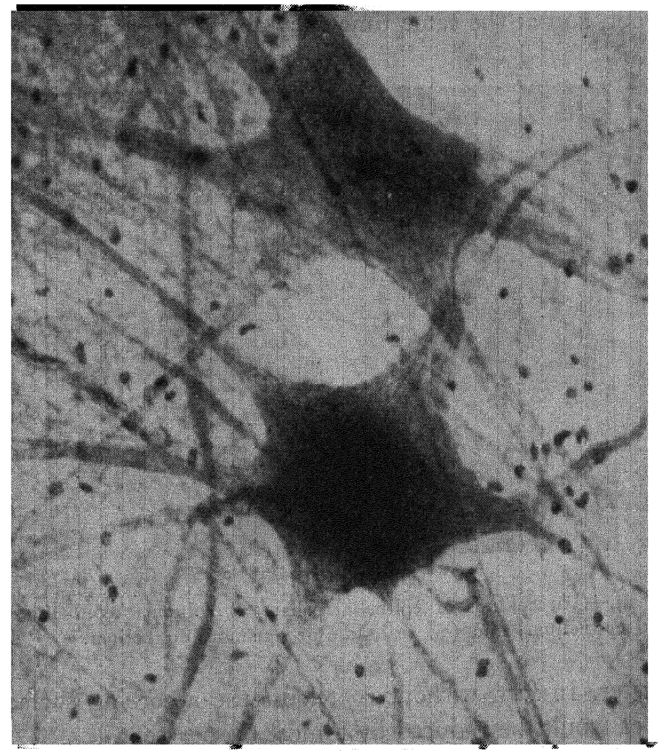
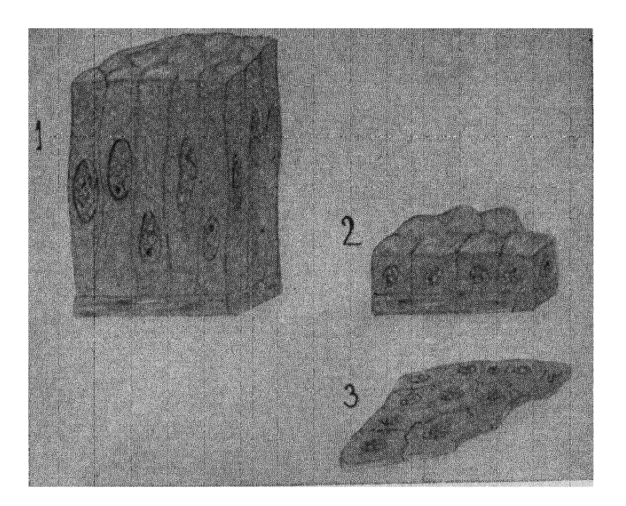


FIG. 13.—Two nerve cells in the spinal cord of a cat. Nerve fibers are elongate extensions of such cells, which may reach parts of the body several feet distant from the main part of the cell. The nuclei do not show clearly, due to over-staining.

Likewise among plant cells *form varies according to function. Root-hair cells* (Fig. 15), for example, represent a specialized epithelium, or *epidermis,* which covers the root where the plant absorbs water and mineral salts from the soil. The *body* of a root-hair cell is bricklike, and the many separate "bricks" fit together, covering the surface of the root. But each root-

hair cell also displays an elongate outgrowth—the *root-hair proper.* Each root-hair extends out among the particles of soil, making contact with the soil water. Thus the special form of the root-hair cells enables them to perform a double function. Collectively they provide epithelium for the outer surface of the root, and at the same time they absorb substances from the



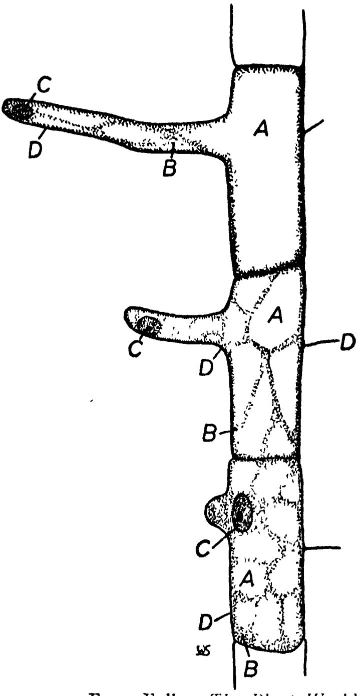
From Best and Taylor, *The Living Body*

FIG. 14.—Three kinds of epithelial cells: (1) columnar epithelium; (2) cuboidal epithelium; and (3) scale-like or squamous epithelium.

soil water. In fact, without root-hairs the absorbing surface of the root would be reduced by almost 90 per cent.

Regardless of their shape, all cells tend to round up into droplike spheres, if freed from various restraining factors. This behavior results from the fact that protoplasm is essentially a *liquid.* All small liquid masses—such as droplets of mercury, or water—behave in this fashion. The rounding results from surface forces which act in the boundary layers of liquids generally. The surface forces in protoplasm are small, relative to those acting upon a drop of water exposed to the air. But the typical cell is a microscopic mass, and most cells do round up like other liquids, unless there are restraining factors.

Many cells are rounded and droplike when first they are formed by cell division, and such cells must expend energy when they distort themselves into another shape. But after a cell has assumed its final form it may retain this shape in a variety of ways. It may surround itself with a rigid or semi-rigid non-living coating, which holds the protoplasm in a definite mold; or it may construct a delicate intracellular skeleton to support the protoplasm (Fig. 16). Also cells may stabilize their shape by a gelling of the protoplasm, or merely by pressure from surrounding cells.



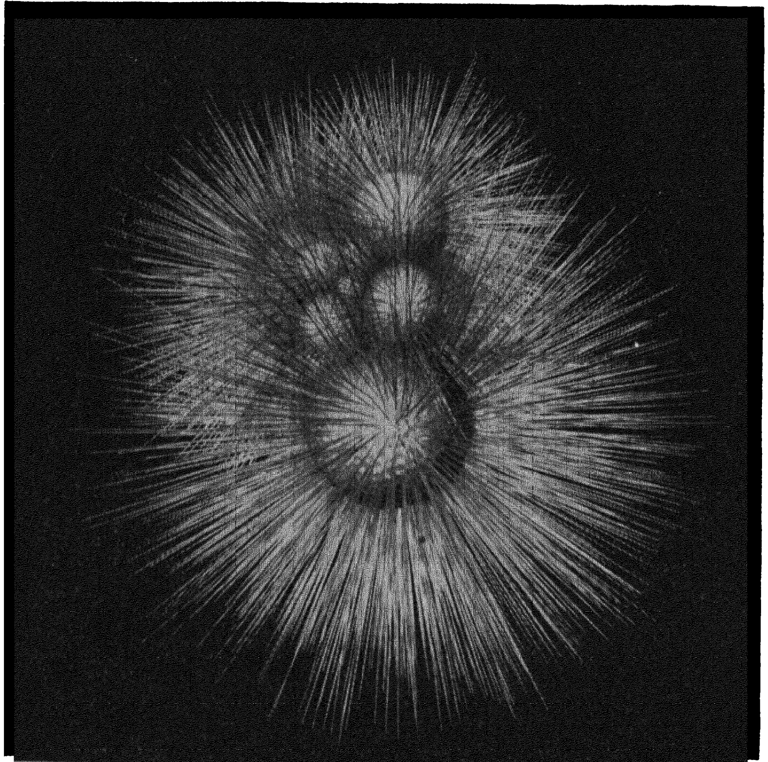
From Fuller, *The Plant World*

FIG. 15.—Epidermal cells of root showing development of root hairs

A. Vacuoles C. Nucleus
B. Cytoplasm D. Cell walls

Intracellular Structure. Under the microscope, the cytoplasm and nucleus usually display a complex internal structure (Fig. 17), although not all the delicate features of intracellular structure can be seen clearly while the cell is still alive. Frequently it is necessary to *kill* and *fix* the cell, using chemicals to solidify and stabilize the structure; and usually the cell must be *stained* with dyes, which color the internal structures differently. Also large masses of cells are too opaque to study directly under the microscope, so that most tissues must be cut, or *sectioned*, into thin transparent slices, before they can be studied. To some extent these various treatments must change the living protoplasmic structure, and consequently it is important to check such observations thoroughly, and to obtain all possible data from the living cell.

The Nucleus. In the living cell, even the nucleus is hard to see, although usually a good microscopist can bring it into view. The difficulty arises from the fact that the nuclear and cytoplasmic parts of the protoplasm have many common prop-



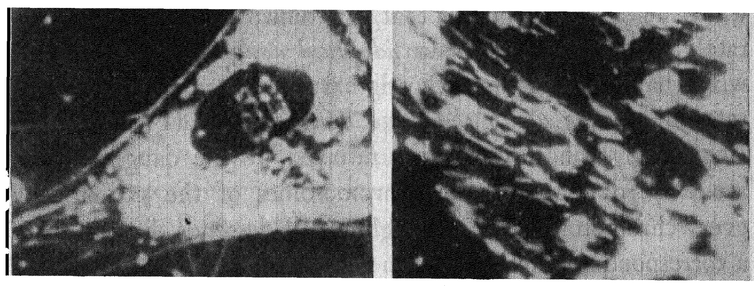
Courtesy of American Museum of Natural History, New York

FIG. 16.—The calcareous intracellular skeletons of a group of one-celled animals, Globigerina. Photograph of a glass model by Herman Mueller.

erties. Typically both are colorless, transparent, and fluid; and both have a broadly comparable chemical constitution (Chap. 4). Consequently it is not surprising to find that the optical differentiation between the nucleus and cytoplasm is often very slight.

In a stained cell, however, the nucleus is plainly visible, since the nucleus usually takes on a deeper color than the cytoplasm.

However, the dye does not stain all parts of the nucleus equally, but colors a number of granules, which appear to be suspended in an unstained background. These stainable granules, which are characteristic of nuclei generally, are called *chromatin* granules; and the unstained "background" material of the nucleus is referred to as *nucleoplasm*. The chromatin granules sometimes appear in countless numbers, as barely visible particles



Courtesy of Dr. R. G. Canti

A B

FIG. 17.—A, a connective tissue cell growing in tissue culture, as seen with a *darkfield* microscope. The dark oval body is the nucleus, in which there are two nucleoli. The cell membrane shows most clearly along the upper margin of the cell; and a multitude of particles cloud the cytoplasm. B, very highly magnified part of the cytoplasm of the same cell. The elongate threads are mitochondria (chondriosomes), and the oval, or rounded, bodies are fat globules.

clouding the nucleoplasm; or they may be fewer and coarser. The chromatin may be arranged to simulate a network, or it may be scattered evenly or unevenly. In fact, the disposition of the chromatin appears to vary from cell to cell, and even in the same cell, when different fixing and staining reagents are employed.

Chromatin is composed mainly of *nucleoprotein* substances (see Chap. 4); but there is an almost endless variety of nucleoproteins. Very probably the chromatin of different cells is specifically different, at least as to the finer details of chemical structure. There is, however, a recently developed staining method, called the *Feulgen reaction,* which permits chromatin to be identified with a fair degree of certainty.

The chromatin part of the nucleus is of great importance to the cell. Whenever a cell divides, the chromatin is carefully assembled and subdivided equally between the daughter cells. Early in division, all the chromatin becomes aggregated, forming a definite number of rodlike bodies, called *chromosomes* (Fig. 26, 7), and the chromosomes line up precisely in the center of the cell (Fig. 26, 9). Before this time, however, each chromosome splits lengthwise into two identical *daughter chromosomes*, which lie so close together that it is difficult to see them separately. Subsequently, the two *identical daughter chromosomes*, which have arisen from each original chromosome, always separate, and *never go to the same daughter cell* (Fig. 26, 10). Accordingly the chromosomes received by the daughter cells are exact duplicates of the chromosomes of the parent cell: every chromosome in each daughter cell descends directly from a corresponding chromosome in the parent cell.

Cell components other than the chromosomes are usually apportioned between the daughter cells with approximate equality, but only chromosomes are distributed by a special mechanism which guarantees an *exactly* equal apportionment. This indicates that the chromosomes are particularly important; for it is known that the chromosomes consist of material units, called *genes*—which determine the inheritance of each cell and organism. In short, what the chemist refers to as nucleoprotein, the biologist as chromatin, and the geneticist as genes, in the last analysis are probably the same, or very closely related materials (Chap. 25).

Many nuclei contain one to several smaller bodies—called *nucleoli*—suspended in the nuclear matrix (Fig. 17). Nucleoli are not stained by the Feulgen technique, and are not regarded as aggregations of chromatin. The evidence indicates that: (a) the number of nucleoli is definite for the cells of each species; (b) the old nucleoli disintegrate each time a cell divides; and (c) the new nucleoli arise at fixed points on specific chromosomes. However, little or nothing is known as regards the specific functional significance of nucleoli.

In size, form, and position, nuclei are widely variable; but usually the nucleus is rounded, and lies near the center of the cell. The relative size of the nucleus also varies, from a small fraction to almost the whole cell volume. In any one kind of cell, however, the ratio of the nuclear and cytoplasmic volumes appears to remain quite constant.

The bacteria and blue-green algae are considered as very primitive cells, because they lack definitely organized nuclei (Figs. 9 and 11). In such cells, the chromatin granules, which are called *chromidia*, are scattered more or less widely throughout the cytoplasm. Among the blue-green algae, there is a tendency for the chromidia to be aggregated toward the center of the cell (Fig. 9), and it seems probable that the chromidial, or scattered type of nucleus, represents an early evolutionary stage which preceded the segregation of the chromatin material within a definite nuclear membrane.

The Cytoplasm. All the protoplasm of the cell exclusive of the nucleus, is the cytoplasm. Essentially the cytoplasm appears to be a clear, optically homogeneous liquid, although in many cells a variety of microscopically visible bodies including *granules*, *fibrils*, *crystals*, and *vacuoles* can be seen in the clear cytoplasmic matrix. Probably not all the bodies visible in the cytoplasm are to be regarded as essential parts of the living protoplasm. In certain cases, the cell may lose these visible bodies without suffering any obvious functional impairment. An Amoeba, for example, can be centrifuged so strongly that all the visible elements are thrown forth through the plasma membrane—the heavier granules and crystals from one end of the cell, and the lighter bodies from the other. Such a cell displays a perfectly clear, optically empty cytoplasm, surrounding the conspicuous nucleus. Nevertheless this Amoeba continues to move and to take in food with only slightly diminished vigor; and in about 24 hours the Amoeba regenerates its missing structures.

This experiment does not prove that the visible bodies of the cytoplasm may not be functionally important, or that they may not represent specialized parts of the cytoplasm itself. It merely

emphasizes the essentiality of the clear part of the cytoplasm. This clear cytoplasm, together with its complement of nuclear material, seems to possess a large part of the potentiality of the cell to perpetuate its structure and activity.

Cytoplasmic Bodies. A wide variety of *formed bodies* can be seen in the cytoplasm of different cells, but only the most generally occurring types will be mentioned at this time.

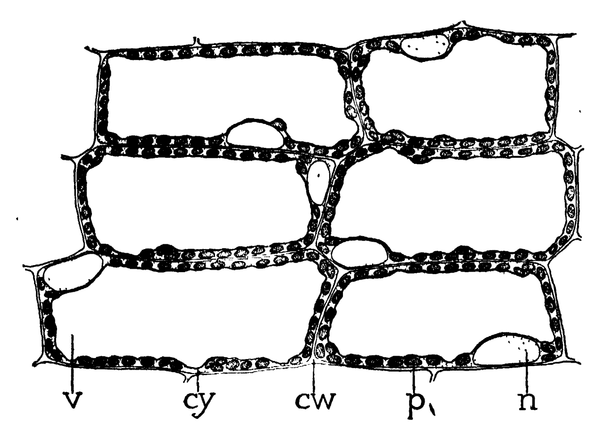


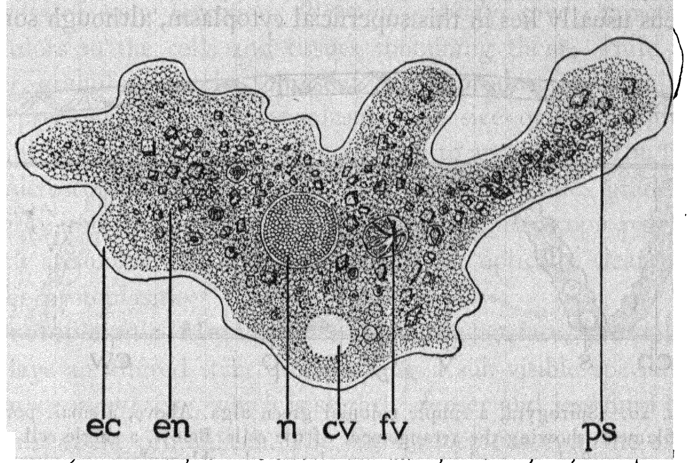
FIG. 18.—Cells of the leaf of a plant (Elodea), in the living condition. v, vacuole; cy, cytoplasm; cw, cell wall; p, plastid (chloroplast); n, nucleus.

Typical *plastids* are pigmented bodies, which usually display a fixed and definite form. The most widely distributed plastids are the green ones, called *chloroplasts*, which are found in many plant cells (Fig. 18). Chloroplasts account for the green coloration of typical plants, and without chloroplasts plants are not able to utilize the energy of sunlight for chemical synthesis (see Chap. 8).

Chondriosomes and *Golgi bodies* display a less definite and more changeable form than plastids, varying widely from dispersed granules or rodlets (Fig. 17) to rather intricate networks. Both chondriosomes and Golgi bodies have been found in many kinds of cells, but it is not certain that all the bodies designated by each of these names are similar in nature. The functions of mitochondria and Golgi bodies are not definitely

known, although perhaps they may be focal points for chemical syntheses.

Typical *vacuoles* appear in the cytoplasm as clear fluid-filled vesicles, although some vacuoles may contain particles of solid matter in addition to the clear fluid. One very common type of vacuole is the *contractile vacuole,* found in fresh-water animal cells such as Amoeba (Fig. 19). In the Amoeba, the con-



ectoplasm; cv, contractile vacuole; fv, food vacuole; ps, pseudopodium.

tractile vacuole takes the form of a clear round body which gradually grows larger. Soon a contractile vacuole reaches a maximum size; and then it suddenly disappears, emptying its contents outside of the Amoeba, through the surface membranes. The contractile vacuole serves chiefly to extract water from the cytoplasm and to pump it outside the cell. This work must go on continually, because water constantly seeps into the cell from the outside medium. If the contractile vacuole fails to function, the Amoeba begins to swell, and soon may reach the bursting point (Chap. 6).

The *food vacuole* is another type of vacuole found in Amoeba (Fig. 19) and other one-celled *animals.* Food vacuoles contain particles of solid food as well as water taken in from the environment. In the food vacuole, the organic food substances

are gradually digested and prepared for absorption into the other parts of the cell.

Cell sap vacuoles, which are found in all large plant cells (Figs. 15 and 18), contain *cell sap,* an aqueous solution of mineral salts. Usually a large cell sap vacuole lies at the very center of the plant cell, so that the cytoplasm occupies only a relatively thin layer between the vacuole and the cell wall (Fig. 18). The nucleus usually lies in this superficial cytoplasm, although some-

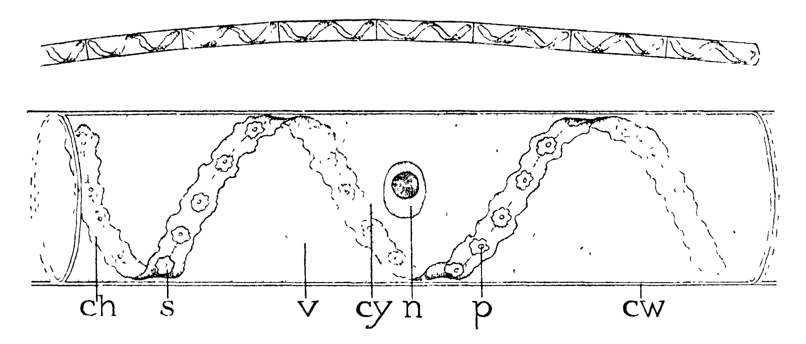


FIG. 20.—Spirogyra, a simple colonial green alga. Above, a small portion of a filament, showing the arrangement of the cells. Below, a single cell more highly magnified. n, nucleus, cy, cytoplasm, ch, chloroplast, p, pyrenoid, s, starch grain; v, vacuole, cw, cell wall.

times it is found at the center of the vacuole, suspended by strands of cytoplasm which stretch across the vacuolar space (Fig. 20). Cell sap vacuoles play an important role in controlling the water balance in plant cells and tissues (Chap. 6).

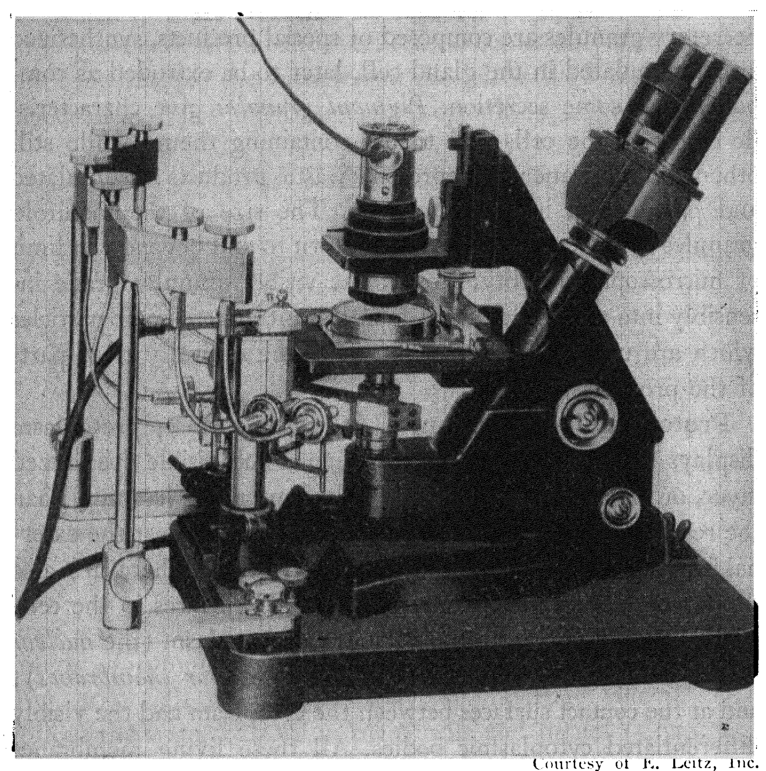
Fibrils are various kinds of delicate threads which can be seen in the cytoplasm of many cells, especially in tissues which have been fixed and stained. Some of the fibrils seen in fixed tissues are probably artificial coagulation patterns produced by the action of the fixing reagents; but fibrils do exist in many living cells—at least on an ultramicroscopic scale. In muscle tissue, for example, longitudinal fibrils can always be demonstrated (Fig. 167); and very probably these *myofibrils* determine the contractibility of the muscle. Temporary fibrillar structures, such as *spindle fibers* (p. 48) also appear at the time of division in practically every kind of cell.

Granules of more or less inert materials are found in virtually every kind of cell. Many of these granules represent stored materials—such as starch grains (in plant cells), fat droplets or glycogen grains (in animal cells), and yolk granules (in egg cells). Others, particularly in gland cells, are *secretory granules.* Secretory granules are composed of special products, synthesized and accumulated in the gland cell, later to be extruded as components of some secretion. *Pigment granules* give characteristic colors to the cells and tissues containing them; while still other granules merely represent waste products accumulated and precipitated in the cytoplasm. The size of the manifold granules in the cytoplasm extends down to and beyond the limit of microscopic visibility. In fact the visible granules grade insensibly into the range of the countless ultramicroscopic particles which are universally present even in the optically clear parts of the protoplasm.

Protoplasmic Membranes. At every surface, protoplasm displays an altered structure, forming a sub-visible specialized layer, or *membrane,* which is slightly denser and less fluid than the rest of the protoplasm. The *plasma membrane,* at the external surface of the cytoplasm, is such a layer. There are also similar membranes at all internally placed surfaces in the cell: at the boundary between the nucleus and cytoplasm (the *nuclear membrane*); bordering each vacuole (*vacuolar membranes*); and at the contact surfaces between the cytoplasm and the visibly differentiated cytoplasmic bodies. All these living membranes possess a number of unique and important properties, but these properties have been studied extensively only in the case of the plasma membrane.

The Plasma Membrane. The plasma membrane is so exceedingly thin that it is not microscopically visible as a separate structure. It appears merely as the external boundary of the cytoplasm. Nevertheless the plasma membrane has great functional importance; for the plasma membrane limits and controls the passage of dissolved substances into and out of the cell.

Because the plasma membrane is not visible as a separate structure, many earlier biologists doubted its existence. These workers compared the cell to a mass of gelatin or other gelated material, in which no differentiated boundary membrane is pres-



Courtesy of E. Leitz, Inc.

FIG. 21.—The Chambers Micromanipulator mounted for use with an inverted microscope. This apparatus is used to inject fluid reagents into the cytoplasm or nucleus of the cell, as well as to dissect the cell.

ent. To explain the fact that certain substances—particularly dye-stuffs like *phenol red*—fail to penetrate the cell from a surrounding solution, it was said that the protoplasm has no "chemical affinity" for the dyes in question.

Proof as to the existence of the plasma membrane was finally obtained by means of *micro-injection experiments* (Fig. 21). If a phenol red solution is micro-injected into the cytoplasm, it

does color the protoplasm. In fact the injected dye spreads throughout the whole cytoplasm; but when it reaches the boundary surface, it cannot pass out of the cell. Therefore it is certain that the boundary layer is different from the internal cytoplasm, and this differentiated surface layer of the cytoplasm is called the *plasma membrane*. The plasma membrane prevents the molecules of phenol red from entering the cell from a surrounding solution, and likewise it prevents the dye from leaving the cell once it is placed inside.

The plasma membrane, like other parts of the living protoplasm, displays a well-defined capacity for self-repair. If the cell surface is torn—as for example with a microneedle—the gap seals itself spontaneously, provided the tear is not too drastic. But if a very extensive rent is torn in the plasma membrane, a visible wave of disintegration sweeps over the surface of the cell; and within a few seconds all parts of the protoplasm disintegrate. This experiment shows that the plasma membrane is an integral part of the living protoplasm without which the cell cannot remain alive.

Non-protoplasmic, or Extraneous Membranes. In most cases the cell is covered by some sort of extraneous membrane, which lies in contact with the outer surface of the plasma membrane. Such non-living covers protect the protoplasm from mechanical injury, and help to maintain the characteristic shape of the particular cell. Extraneous membranes are usually thick enough to be visible under the microscope, and are composed of inert substances which have been synthesized by the protoplasm and deposited at the external surface.

The extraneous membranes of plant and animal cells are generally quite different, and consequently they are given different names. In the case of plant cells it is customary to speak of the *cell wall;* and in the case of animal cells, one speaks of the *pellicle*, or *cuticle.*

The cell wall (Figs. 15 and 18) of plant cells is generally stronger, more rigid, and less elastic than the *pellicle* of animal cells—as can be demonstrated by experiments. If plant and

animal cells are placed in distilled water, which tends to make cells swell (Chap. 6), the results are quite different in each case. Animal cells, owing to the greater elasticity and weakness of the pellicle, continue to swell. The cells become larger and larger, until finally they burst. But plant cells swell only slightly, and then they stop. The strength of the cell wall, like that of the casing of an automobile tire, prevents further swelling—despite the fact that the inflation pressure in the plant cell may reach a value of several atmospheres.

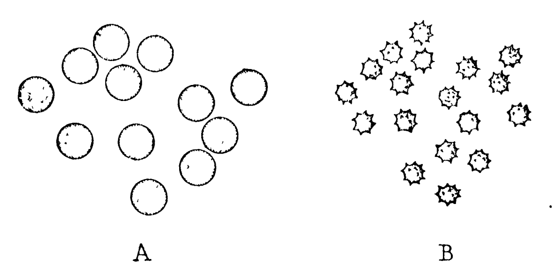


FIG. 22.—The shrinking of animal cells (human red cells). A, unshrunken, B, shrunken—with wrinkled pellicle.

The converse of this experiment demonstrates the greater *rigidity* of the cell wall, as compared to the pellicle. When plant and animal cells are placed in strong salt solutions, which induce the protoplasm to shrink, marked differences are again observed. As the animal cell shrinks, at first the pellicle shrinks along with the protoplasm. But as shrinkage continues the flexible pellicle becomes wrinkled (Fig. 22) and distorted to fit the reduced contour of the cell. In the plant cell, on the other hand, the cell wall does not shrink as the protoplasm shrinks; nor does the cell wall become wrinkled. The protoplasm merely pulls away from the rigid wall and continues to shrink by itself until it occupies only a small part of the original tightly fitting compartment (Fig. 23).

The different *physical* properties of the cell wall and pellicle reflect a fundamental difference of *chemical* constitution. The cell wall of the typical plant cell is composed mainly of a *carbohydrate* substance, *cellulose*, which is the special component of

all "woody" materials. But the pellicle in all typical animal cells is composed mainly of *protein* substances (Chap. 4).

Extraneous material, found between the cells of certain tissues, is designated generally as *intercellular matrix*. In some tissues (e.g., bone and cartilage) the matrix is more abundant than the protoplasm (Fig. 170). Like the cell wall or pellicle, the matrix is secreted by the cells which it surrounds, and the matrix is not part of the protoplasm. Even in tissues possessing

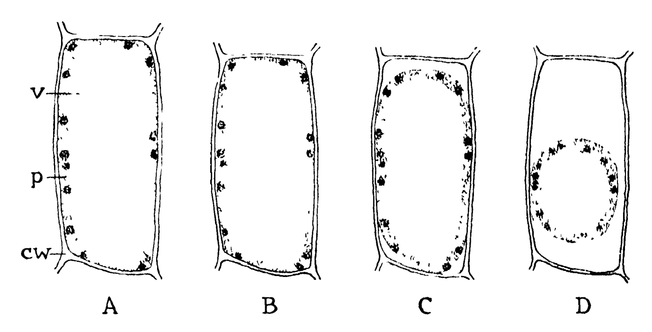


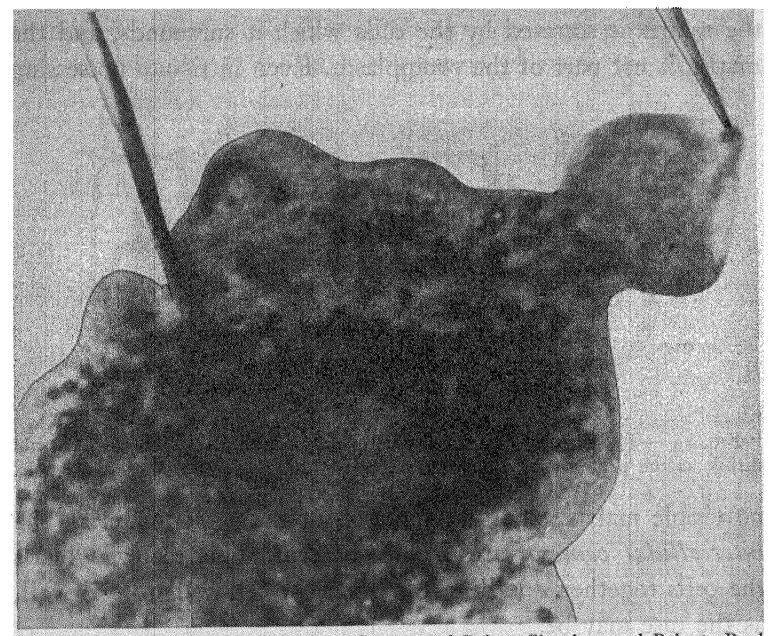
FIG. 23.—The shrinking of a plant cell. The cell wall is rigid, and does not shrink as the protoplasm shrinks. CW, cell wall; p, protoplasm; v, vacuole.

no visible matrix, small amounts of an analogous material, the *intercellular cement*, are usually present. This material binds the cells together—pellicle to pellicle, or cell wall to cell wall, as the case may be.

The non-living nature of extraneous membranes and matrices generally is emphasized by the fact that they are not essential to the life of the cell. By microdissection and other techniques, the cell wall or pellicle can be removed from a number of plant or animal cells. Such naked cells are more vulnerable to mechanical injury, and may fail to maintain their normal shape, but they continue to live. In time, such naked cells may resecrete the missing protective material.

Functional Role of the Nucleus. By means of microneedles, the nucleus can be removed from a one-celled animal like Amoeba without damaging the cytoplasm (Fig. 24). Such an enucleated cell continues to perform certain vital functions *for*

a limited time. Without a nucleus the Amoeba continues to move, responding to stimuli from nearby food; and sometimes the specimen will even ingest and digest some food. But without a nucleus, the Amoeba *does not grow, and cannot maintain its existing structure.* Gradually the enucleated cell be-



Courtesy of Robert Chambers and Roberts Rugh

FIG. 24.—Using microneedles to remove the nucleus from an Amoeba. The left needle holds the Amoeba while the right one pulls out the nucleus through the cell membrane.

comes smaller, and finally, after about 24 hours, it disintegrates.

Such enucleation experiments indicate that the nucleus is necessary if a cell is to maintain its *constructive metabolism,* synthesizing new substances for growth and maintenance. Some *synthetic reactions* (Chap. 4) probably go on in the cytoplasm as well as in the nucleus, but the nucleus seems to be necessary if constructive metabolism is to continue. *Destructive metabolism,* however, appears to go on in the cytoplasm more or less independently of the nucleus.

The *importance of the nucleus in constructive metabolism* is emphasized by other observations. The nucleus usually migrates to any part of a cell where active synthesis is occurring; and gland cells—in which constructive metabolism goes on very rapidly—tend to possess exceptionally large or lobulated nuclei, which expose a maximum of surface to the surrounding cytoplasm (Fig. 25).

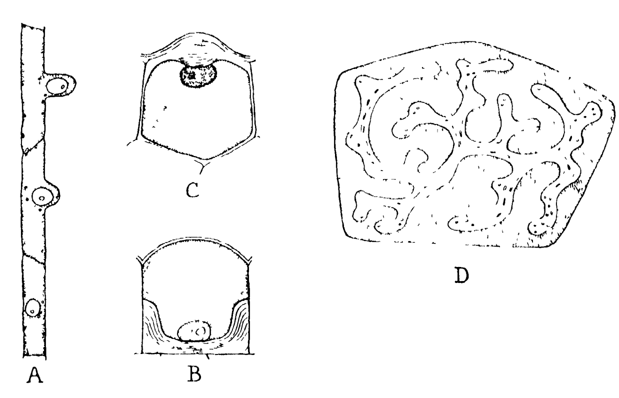


FIG. 25.—The nucleus is concerned with synthetic processes in cells. A, growth of root-hairs from epidermal cells of root of plant, note the location of the nuclei close to the points of rapid growth. B, C, plant cells synthesizing local thickenings of the cell walls, with the nucleus close to the point of special thickening in each case. D, a cell of the silk-gland of a caterpillar, with a large lobulated nucleus. (A, B, and C after Haberlandt, D, after Korschelt.)

The Cell and the Organism. In the simplest organisms the whole body consists of a single cell; and within the limits of such a cell there may be a fairly complex differentiation of structures, especially in the case of animal cells. The nutrition of a *typical animal* (Chap. 7), even in unicellular forms, presupposes a capacity to *sense* the location of food, to *move* toward food, and to *ingest*, *digest* and *absorb* the food; and these reactions require a complex structural organization even in the single cell.

The unicellular condition has limitations, however, particularly as regards the maximum size to which the organism can grow (p. 21). Larger organisms—up to a fairly huge limit—possess many obvious biological advantages. Large organisms

are less vulnerable to small environmental forces; and they are less at the mercy of smaller enemies. Bacteria, because of their smallness, are continually buffeted from side to side by the random bombardment of the molecules of the water in which they live; but the greater bulk of the larger aquatic forms makes them immune to such small forces. When a small insect, or other animal, falls upon still water, it may be caught and torn by surface-tension; but larger animals may clamber in and out of water without any fear of such a puny force. A salmon breasts the strongest stream, impossible for even the fastest-swimming protozoan; while an elephant may easily uproot a tree which previously was the home of many smaller creatures.

The advantages of greater size were gained by plants and animals mainly through the evolution of *cell aggregates.* In simplest form such aggregates are mere colonies, with the individual cells independent of each other (Fig. 20). But colonial forms were followed in evolution by *multicellular organisms,* in which the many cells are of different kinds, each being fitted for some special function. Accordingly the different cells of the multicellular organism are dependent upon each other to a very significant degree.

Most multicellular organisms arose, not by the coming together of previously dissociated cells, but by the staying together of cells derived by division from a single parent cell. In fact virtually all multicellular plants and animals return to the unicellular condition each time a new individual is conceived. Among plants and animals generally all the cells of each offspring are derived by division from a *fertilized egg-cell.*

In multicellular organisms each kind of cell, taken *as a group,* constitutes a different *tissue* (e.g., bone and muscle, in animals; or xylem and epidermis, in plants). The tissues in turn compose the *organs* (such as the stomach of an animal, or the leaf of a plant)—each organ being fabricated of several different tissues. Finally, the organs themselves are grouped into *organ systems* (such as the digestive system, or the nervous system), each system subserving some general function in the nutrition, responsiveness or reproduction of the organism as a whole.

In higher organisms, the distribution of substances is effected by body fluids (such as blood, lymph, or sap) which flow throughout the body in definite channels. Likewise, the nervous system effects an integrated behavior of the body parts in higher animals generally. These connections enable the cells, tissues, and organs of the multicellular body to act together as a unified whole—the *organism*. But *whatever the organism does is done by its cells*, and the noncellular parts of an organism are lifeless products and passive tools subserving the activities of the living cells. Thus the life of the organism is to be considered as the sum total of the vital activities of its component cells. To consider that the organism is "something more than the sum of its cells" is like considering that a machine is something more than the total of its parts. Without question the properties of the whole machine are determined by the relations, as well as by the structure of the isolated parts—and how the parts are fitted and linked together is just as important as how each is formed individually. Likewise the activities of an organism result from the interaction, rather than from the independent action, of the component cells, organs, and organ systems.

The tissue cells of a complex animal subordinate themselves to the functions of the whole organism; but all the cells are individually alive, and some retain an unlimited potentiality for growth and multiplication. This can be shown by the technique of tissue culture. In this technique a small piece, usually of embryonic tissue, is placed in a nutrient medium, such as the blood plasma of the same animal. Optimum conditions are provided for the cells by changing the medium at frequent intervals, meanwhile trimming away excess quantities of tissue as growth continues. The utmost care to prevent bacterial contamination must be taken during all these operations.

In tissue culture, some cells retain their characteristic form and activity, and their capacity to grow quite indefinitely (Fig. 17). At the Rockefeller Institute, for example, a piece of heart tissue, taken from a chick embryo, was cultured for more than twenty years. In this tissue some of the cells remained motile and continued to grow throughout the whole period. In fact,

if all this growing tissue could have been saved and provided with good conditions, the accrued amount of new tissue would now be many times the volume of this earth.

The Cell Principle. The *cell principle* has gradually developed from the cell hypothesis, and now it has attained a very fundamental importance in biology. This development may be summarized as follows:

1. Plant and animal bodies, aside from minor exceptions, are composed of one or more cells. Among the first to emphasize this generalization were a botanist, Mathias Schleiden (1838), and a zoologist, Theodor Schwann (1839), who submitted the cell hypothesis almost simultaneously. Much earlier Robert Hooke (1665) first observed plant cells, and Anton Leeuwenhoek (1660) first saw animal cells. However, these early investigators could not have realized the general occurrence and wide significance of the cell.

2. The essential living part of every cell is its protoplasm. In the early development of the cell hypothesis, the cell wall (or the pellicle) was thought to be more important than the protoplasm; and it was not until 1861 that Max Schultze recognized that the protoplasm alone displays the essential attributes of life, in both plant and animal cells.

3. New cells arise only by division from pre-existing parent cells—at least under conditions as they exist today. Accordingly each species of plant and animal represents an unbroken cell-lineage extending back into ancient time. The first of these conclusions was stated clearly, by Virchow in 1855; and the second derives from the work of August Weismann, in the latter part of the nineteenth century.

4. Each cell—so long as it retains its capacity for growth and multiplication—must be considered as an integral living unit. This conclusion was clinched by tissue culture experiments, which were begun by Harrison in 1912.

5. The life of the whole organism represents the sum total of the cooperative life of the component cells. This conclusion is scarcely susceptible to proof, but is a viewpoint supported by a wide variety of observations and experiments.

TEST QUESTIONS

1. List the features which are possessed by typical cells generally. Make a fully labelled sketch of any cell which displays all these features.
2. Explain why each of the following is not to be regarded as a typical cell: (a) any bacterium; (b) the slime mold; (c) a skeletal muscle fiber. Make labelled sketches to illustrate the points in question.
3. Cite examples (including the dimensions):
   a. an extremely small cell;
   b. an extremely large cell;
   c. a cell of average size.
4. Explain how and why cells generally cannot grow beyond a certain definite limit.
5. Why do cells tend to assume a droplike form when constraining factors are absent? Explain.
6. Cite two examples to illustrate the general rule that the form of a cell is generally related to its function.
7. Distinguish between:
   a. chromatin and chromosomes;
   b. chromatin and chromidia.
8. Cite evidence indicating that the chromatin part of the protoplasm is very essential in every cell.
9. Specify five kinds of *cytoplasmic bodies* and explain how each is identified.
10. Cite an experiment which shows that the clear matrix of the cytoplasm determines the formation of many of the cytoplasmic bodies.
11. What properties of the plasma membrane distinguish this membrane from such extraneous membranes as the pellicle and cell wall?
12. Describe the micro-injection technique and explain how it has been used to prove the existence of the plasma membrane.
13. Define the terms "cell wall" and "pellicle"; specify at least three differences between these two kinds of membranes.
14. Cite an experiment which demonstrates the general importance of the nucleus in the metabolic activities of the cell. What other evidence tends to substantiate the conclusion drawn from the experiment?

15. Distinguish between an organ and an organism.
16. Explain the technique of tissue culture; what important conclusion has been derived from tissue culture experiments?

FURTHER READINGS

1. *Unresting Cells*, by R. W. Gerard; New York, 1940.
2. *The Physical Basis of Life*, by Edmund B. Wilson; New Haven, 1923.

CHAPTER 3

CELL DIVISION IN RELATION TO REPRODUCTION

SOONER or later each kind of cell reaches a size where it must either stop growing, or divide. If it is to be division, the cell begins to undergo a drastic reorganization, and during the division period the nucleus plays a dominant role.

Biologists are generally agreed that new cells arise solely by division from pre-existing parent cells, at least under conditions as they exist today. Accordingly cell division provides the underlying basis for all forms of reproduction—sexual as well as asexual—in every kind of plant and animal. Cell division also provides a basic mechanism for the transmission of hereditary qualities from cell generation to cell generation, and from generation to generation of the whole organism.

In man and in multicellular animals generally, all the cells of the body arise by division from a single embryonic cell, the *fertilized egg*. This fertilized egg is formed by the fusion of two cells, an *egg* and a *sperm*, which likewise arose by division from the cells of the parent organisms. The same situation also holds true for most multicellular plants. However, the cells of some plants are formed by the multiplication of another kind of cell, called a *spore*, which differs somewhat from an egg-cell (Chap. 11).

In both plants and animals a great majority of the cells are produced in common fashion, by a type of cell division called *mitosis*, which was described briefly in the last chapter. But it is necessary to realize that certain cells—especially the *eggs* and *sperm* in animals, and the *spores* in plants, are produced by a

somewhat different type of cell division, called *meiosis*. These two types of division are the only *normal* methods of division which occur in nature. Generally speaking the *body cells* of the organism are formed by *mitosis*, but the *eggs* and *sperm* (in animals) and the *spores* (in plants) are produced by *meiosis*.

Mitotic Cell Division. This common type of cell division is one of the most complex and at the same time one of the most regular processes in living things. The microscopically visible aspects of mitosis are studied most conveniently in cells which have been fixed, sectioned, and stained. This method has some obvious disadvantages: it is not possible to follow the sequence of events after the cell has been killed; and it is difficult to know how accurately the fixed and stained material represents the living structures. In a few cases, however, all the essential features of mitosis can be observed in living cells; and such observations confirm the general conclusions drawn from a study of fixed materials. Each cell as seen in a fixed section is like a "snapshot" taken at a particular moment in a series of events. Thus by arranging the "snapshots" in correct sequence, it is possible to reconstruct a "moving picture" of the whole procedure.

The minor details of mitosis differ somewhat in different kinds of cells, although the essential features are the same in all. First to be studied will be the rapidly dividing cells in the growing tip of the root of the onion, which are typical of *plant cells* generally.

When the cell is not dividing, the nucleus is delimited from the cytoplasm by a definite nuclear membrane. The chromatin tends to be invisible in the living nucleus, but in stained sections it appears usually as a fine, irregular network (Fig. 26). One of the first visible signs of mitosis is the aggregation of the chromatin into a number of long slender threads, the *chromosomes* (Figs. 26 and 27). In the onion there are always 16 chromosomes in each cell, and in other species there is also a definite and characteristic chromosome number. Soon the thread-like chromosomes begin to contract and gradually they grow shorter and thicker. While this is occurring, or even earlier,

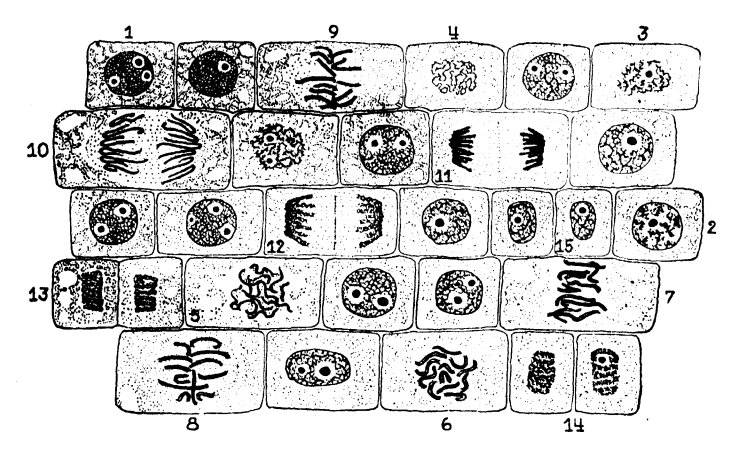


FIG. 26.—Portion of section of root-tip of onion, fixed and stained, showing cells in various stages of mitosis. 1, intermitotic or "resting" stage; 2-7, prophases; 8, 9, metaphases; 10, anaphase; 11-14, telophases; 15, intermitotic stage just after completion of mitosis.

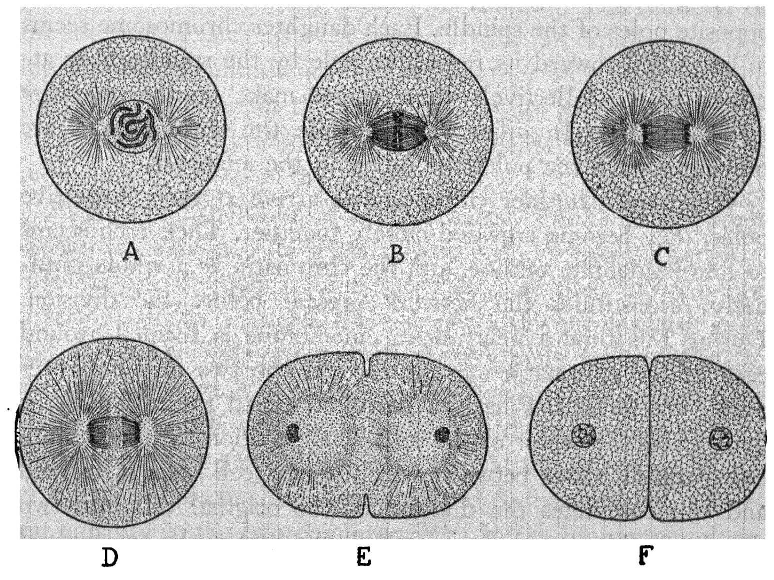


FIG. 27.—Echinoderm egg-cells, fixed and stained, in various stages of mitotic division. A, prophase; B, metaphase; C, anaphase; D, early telophase; E, later telophase, with cleavage of the cytoplasm beginning; F, intermitotic stage just after completion of division. (Adapted from Fry.)

each chromosome splits lengthwise into two exactly similar halves—the *daughter chromosomes*. Also during this stage, the nuclear membrane disappears completely, leaving the chromosomes free in the cytoplasm. Then there appears in the nuclear region a spindle-shaped group of fibers, which converge toward opposite ends of the cell. Some of these fibers are attached to the chromosomes—one to each of the daughter chromosomes—while others run directly from pole to pole in the *spindle*. All of these stages together constitute the *prophase* of mitosis (Fig. 26, 2-7).

The chromosomes now take up a position on the spindle, halfway between the poles, in a plane passing through the center of the cell. This short but definite stage is called the *metaphase* (Fig. 26, 8-9).

The two equivalent daughter chromosomes, formed by the splitting of each original parent chromosome, now move toward opposite poles of the spindle. Each daughter chromosome seems to be pulled toward its respective pole by the spindle fiber attached to it. Collectively these stages make up the *anaphase* (Fig. 26, 10). In other words, while the chromosomes are moving toward the poles the cell is in the anaphase.

When the daughter chromosomes arrive at their respective poles, they become crowded closely together. Then each seems to lose its definite outline, and the chromatin as a whole gradually reconstitutes the network present before the division. During this time a new nuclear membrane is formed around each of the chromatin aggregates, and the two new daughter nuclei are formed. Finally a partition, called the *cell plate*, is built across the center of the cell. This partition then splits into two parallel plates between which a new cell wall is formed and this completes the division of the original cell into two daughters. The stages during which the new nuclei are formed from the two groups of daughter chromosomes and the cytoplasm is divided between the two daughter cells, make up the *telophase* of mitosis (Fig. 26, 11-14).

In the cells of *higher animals* the visible aspects of mitosis are further complicated by the presence of two large radiate

structures, called *asters*. These appear in the cytoplasm, one at each end of the spindle (Fig. 27). The asters enlarge at telephase until they occupy the entire cell outside of the spindle. At the center of each aster there is a spherical body, called the *centriole*, toward which the spindle and astral fibers converge. In most animal cells, the centrioles divide toward the end of telophase, and in some cases the two centrioles remain visible during the intermitotic period.

The cytoplasm of the *animal cell* is divided in a different way from that in the plant cell. No cell plate is formed, but during the telophase a *furrow* appears, encircling the equator of the cell. This furrow gradually deepens until it cuts the cytoplasm in two, forming the two daughter cells (Fig. 27, E-F).

The duration of the mitotic process varies in different kinds of cells. It may last a few minutes, or several hours—the prophase and telophase being usually the longest. The duration of the intermitotic stage is even more variable. In rapidly developing tissues, one mitosis may succeed another with practically no interval at all; but in the specialized tissues of a multicellular organism the mature cells may never divide again during the remaining life-time of the individual.

Primitive Forms of Mitosis. Among primitive organisms, especially bacteria, blue-green algae, and Protozoa, the processes of cell division are somewhat simpler than the one just described. In the bacteria there is not a distinct nucleus, since the chromatin granules are distributed more or less equally throughout the cell. Most bacteria are too small to permit clear observation of the chromatin during cell division; but in larger forms there is a general tendency for the chromatin to be aggregated at the equator of the cell and distributed with apparent equality to the two daughter cells. In the blue-green algae, which also lack distinct nuclei, many intergradations are found between this very simple type of mitosis and types which display definite chromosomes which split longitudinally in the usual fashion (Fig. 28). Among the Protozoa the mitotic structures frequently lie entirely inside of the nucleus; or more specifically,

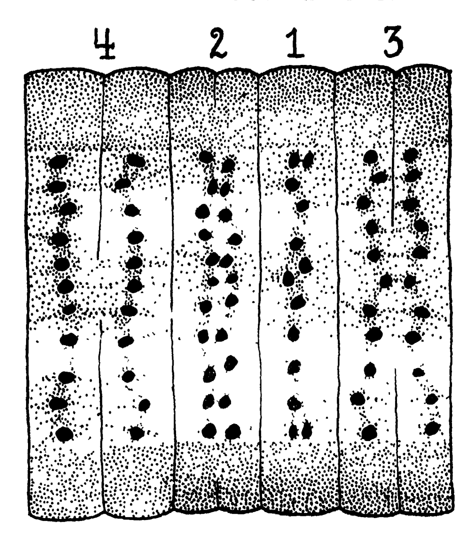


FIG. 28.—Cells of Oscillatoria, a colonial blue-green alga, showing a simple type of mitotic division. 1, 2, 3, 4, successive stages of cell division. (Adapted from Olive.)

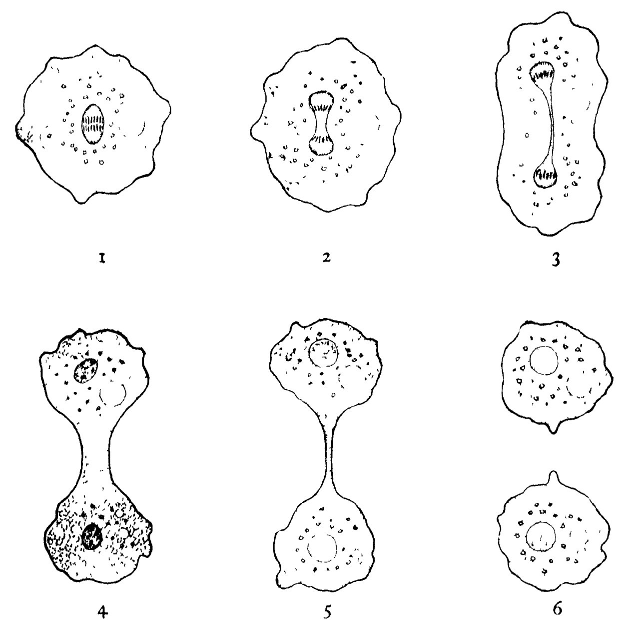


FIG. 29.—Mitosis in an Amoeba. Note that the spindle and chromosomes lie inside the persisting nuclear membrane. 1-6, successive stages.

the chromosomes are formed, split and separated on the spindle, although meanwhile the nuclear membrane persists and continues to surround the whole configuration (Fig. 29).

Significance of Mitosis: Importance of Chromosomes. Viewing the situation as a whole, it seems clear that the behavior of the chromosomes during mitosis is essentially the same in the cells of all multicellular plants and animals—although there are some variations of detail in different kinds of cells, especially as regards the behavior of the nonchromatic parts. At every mitosis, each individual chromosome divides, and one of the two resulting daughter chromosomes passes to each new nucleus. Such a procedure maintains a constant number of chromosomes in the many cells of each different organism. This constant is usually an even number; and this number is the same for all individuals belonging to a given species. The chromosome number varies, in different organisms, from 2 to 200 or more, but usually it lies below 50 (man has 48). Not only the number of chromosomes, but also the size and shape of each chromosome remain constant. Usually the chromosomes of a given species are *individually* distinguishable, and exactly the same set appears at mitosis in all the cells of the individual and of the species. The chromosomes which appear in any cell during the prophase are exactly the same as those which apparently disappeared during the preceding telophase. In some cases the separateness of the chromosomes can be seen at all times, even throughout the *intermitotic* period. But usually this cannot be seen directly, although other evidence indicates that it is true. In other words, each chromosome has a persistent individuality. Each grows during the intermitotic period and each divides at every mitosis. Thus every chromosome maintains its own peculiar composition and structure throughout innumerable cell generations. The essential function of the intricate mechanism of mitosis is to achieve an exactly equal division of the parent chromosomes into two equivalent daughter sets which then are segregated into the two new daughter cells.

The dividing of the other parts of the cell is *not so exactly*

equal: because there is no mechanism to accomplish a precise partitionment of the other parts. If a plant cell, for example, contains a certain number of chloroplasts, *about* half of these usually go to a particular daughter cell. But sometimes the numbers received by the two daughter cells may be quite unequal. The cytoplasm as a whole is divided quite equally in most cells; but in some cases, such as dividing yeasts, one of the daughter cells regularly receives by far the larger share. The significance of mitosis becomes plain when it is realized that each chromosome is the bearer of a specific group of hereditary determinants, called *genes* (Chap. 25). When a cell multiplies by mitosis, its own complex of chromosomes and genes remains unchanged from generation to generation, and consequently there is no change in its intrinsic hereditary potentialities.

Amitosis. In rare instances cells have been observed to divide without forming chromosomes, in which case a cleavage furrow or cell plate cuts directly through the cytoplasm and nucleus. Such cases of *amitotic division* are considered to be abnormal and relatively unimportant, because daughter cells produced by amitosis have lost the potential of remaining alive indefinitely.

Haploidy and Diploidy in Relation to Fertilization. Another important fact about the chromosomes has not been mentioned. When counted and matched against one another, it is usually found that the chromosomes make up a duplicate set. The duplicate, or *diploid,* set of chromosomes possessed by one species of animal is shown in Fig. 30. This relatively simple case shows that the eight chromosomes are really four pairs. Each individual chromosome possesses a *homologous mate* which displays an identical size and shape. Similarly the 16 chromosomes of the onion plant are really 8 pairs; and the 48 chromosomes of man actually represent 24 pairs.

The reason why most of the body cells of plants and animals possess a *diploid* set of chromosomes is relatively simple. The fertilized egg from which all the body cells arise is always formed by the coming together and *fusing of two cells.* A sperm

cell from the male parent always fuses with the *unfertilized* egg cell from the female parent. Thus the diploid set of chromosomes possessed by the *fertilized* egg is really constituted of two single, or *haploid* sets (Fig. 31, A-B). One of these haploid sets was present in the nucleus of the unfertilized egg, and the other was brought in by the nucleus of the sperm cell. When the egg and sperm nuclei finally fuse into one—and this is the essential event of *fertilization*—the nucleus of the fertilized egg becomes diploid, and diploid it remains throughout all subsequent mitotic divisions (Fig. 31, D-E).

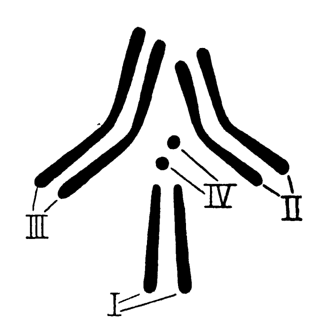


FIG. 30.—Diploid chromosome group of the fruit-fly, Drosophila. The numbers I, II, III, IV indicate the four *pairs* of chromosomes.

Fertilization. Fertilization is a very important process which is encountered in the reproductive cycles of a great majority of plant and animal organisms. The new individual which arises from the fertilized egg possesses chromosomes (and genes) contributed by both the male and female of its parents, and consequently this new individual derives its heritable qualities from both. Sexual forms of reproduction always involve fertilization, and it is only in sexual reproduction that we find *bi-parental* inheritance. Asexual reproductive processes never involve fertilization, and in asexual reproduction inheritance is entirely uniparental. Asexually produced offspring tend to resemble their single parent, and do not display as wide a variability as those which are generated sexually.

Meiotic Cell Division. The real problem as to chromosome numbers is not how the body cells come to be diploid, but how the *eggs* and *sperm* of animals, and the *spores* of plants, come to be *haploid*. This more difficult question took many years to solve. Finally it was learned that these reproductive cells are produced not by mitosis, but by a highly modified type of division, which is called *meiosis*.

One difference between meiosis and mitosis is that meiosis

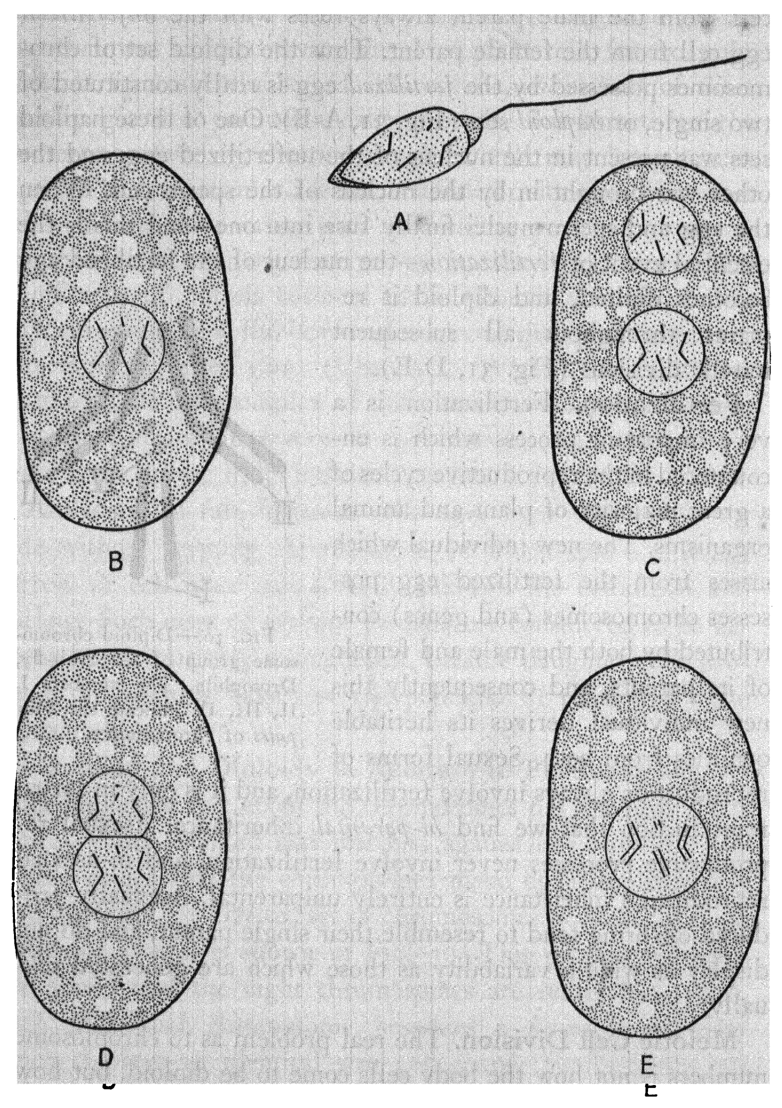


FIG. 31.—Fertilization: origin of diploid cells. A, the haploid sperm cell; B, the haploid (*unfertilized*) egg; C, sperm nucleus (above) migrating toward the egg nucleus; D, sperm and egg nuclei about to fuse; E, the diploid nucleus of the fertilized egg.

involves two quickly succeeding divisions, whereas each single mitotic division is complete unto itself. In meiosis, when the two divisions have been finished, four cells have been produced. The parent cell at the outset of meiosis is always diploid and the four final daughter cells are always haploid. In mitosis, on the other hand, the daughter cells always possess the same number of chromosomes as the parent cell, whether that original number was diploid or, as sometimes is the case, haploid. This and other differences between meiosis and mitosis serve to distinguish clearly between the two processes. Nevertheless, it is important to realize that the two types of division have much in common. In both cases the same four stages—prophase, metaphase, anaphase and telophase—are plainly distinguishable, although in meiosis the steps occur twice. Also the same accessory mechanisms, including spindles, asters and so forth, take part in both kinds of cell division.

The meiotic divisions take place in the *ovaries* or the *testes*, in the case of animals; and in the spore capsules, in the case of plants. At present it will suffice to describe meiosis as it occurs in the testis of a male animal. Later, in connection with the study of heredity, the similar development of eggs in the ovary, and of spores in the sporangium, will also be described.

In the testes of man and other multicellular animals, one finds a numerous group of special cells, called the *spermatogonia* (Fig. 32, A). Sooner or later these cells will give rise to the sperm cells. The *spermatogonia* are *diploid* cells. They have arisen, along with all other cells of the organism, from the repeated mitoses of the original diploid fertilized egg. Furthermore the spermatogonia in the testes may continue to multiply by mitosis, giving rise to a steady supply of more spermatogonia, all diploid.

Finally the germ cells in the testes stop multiplying by mitosis. Now each begins to grow and can be recognized as a *primary spermatocyte* (Fig. 32, B-E). Each primary spermatocyte is destined to undergo only two further divisions and these will be the meiotic divisions. Consequently each primary spermatocyte will form only four sperm cells (Fig. 32, J).

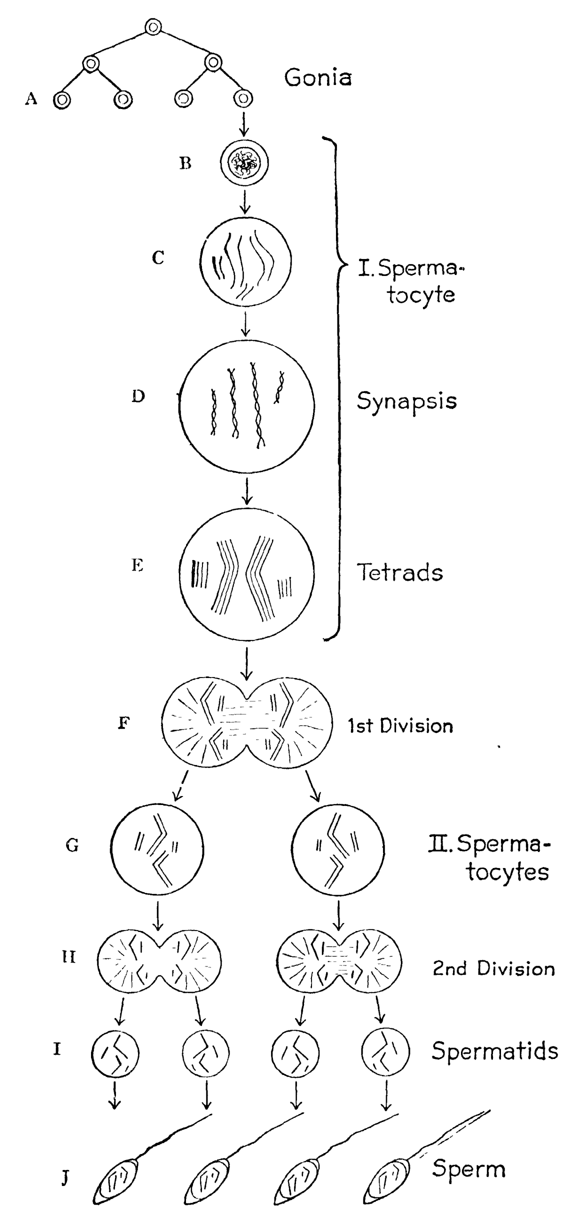


FIG. 32.—Formation of sperm (by meiosis) in the testis of the fruit-fly. Meiosis involves two divisions and in the very long prophase of the first one, synapsis occurs. Each chromosome divides only once during the two divisions of the primary spermatocytes, and consequently the final cells (spermatids and sperm) are haploid.

The prophase of the *first meiotic division* commences almost as soon as the primary spermatocyte begins to enlarge. This prophase differs in two ways from that of an ordinary mitosis. First it endures much longer, usually for days, rather than for hours or minutes, and during all this period, the elongate chromosomes are definitely visible and individually identifiable. Second, in the prophase of the first meiotic division, the two homologous chromosomes of every *pair* always lie side by side, intimately entwined one about the other (Fig. 32, D). This pairing and entwining of homologous chromosomes, which is called *synapsis*, has very real consequences in heredity because, while the pairs of chromosomes are in the synaptic condition, they may mutually exchange a certain number of their genes. Synapsis only occurs during the prophase of the first meiotic division. Usually during ordinary mitosis, the homologous chromosomes behave as independent units and show little or no attraction for each other.

Before metaphase, in the first meiotic division, the pairs of chromosomes have unraveled from synapsis, but still the members of each pair lie side by side. By this time each and every chromosome has divided lengthwise into daughter halves. Consequently at the metaphase of the first meiotic division one sees the chromosomes assembled on the spindle in characteristic quadruple groupings, which are called the *tetrads* (Fig. 32, E).

The splitting of the post-synaptic chromosomes is the only time the chromosomes divide during the whole process of meiosis. In fact the two cell divisions, which follow shortly, serve merely to distribute the chromosomes which exist as soon as the tetrads have been formed (Fig. 32, E-I). And if events proceed in normal fashion, each of the four sperm cells produced by any one spermatocyte is destined to receive just one chromosome from every tetrad (Fig. 32, J).

After the first metaphase, the remaining events of meiosis proceed rapidly. The anaphase and telophase of the first division lead to the formation of two cells, the *secondary spermatocytes*, each receiving half of each tetrad. In other words each secondary spermatocyte receives one of the two *diads* into which

each tetrad has separated (Fig. 32, F-G). But the precise manner in which a tetrad separates into diads appears to be a matter of chance. The two possibilities indicated in Fig. 33 seem to occur with equal frequency.

Without pause, the secondary spermatocytes usually launch into the second meiotic division. In fact the diad chromosomes remain visible, as they quickly pass through prophase and assume the metaphase arrangement on the spindle (Fig. 32, G). Then the anaphases and telophases are completed, and a single chromosome from each of the diads is delivered to each of the four final cells. But here again it is a matter of chance as to which member of a diad pair goes to a particular one of the resulting cells.

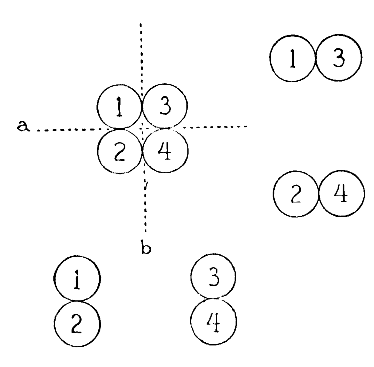


FIG. 33.—Diagram showing how the four chromosomes of any given tetrad may separate during the first meiotic division. Regardless of which of the two possibilities (a or b) occurs, one member of each tetrad eventually reaches every sperm, when the second meiotic division occurs.

The four resulting cells are called *spermatids*. But shortly thereafter, when each has developed an elongate motile flagellum, they are called the *sperm*. As may be seen in Fig. 32, J, each sperm possesses the haploid set of chromosomes which later will be carried to the egg, when fertilization occurs.

Similar processes of meiosis are encountered in the development of the egg cells in female animals, and of spore cells in plants; but the special features of these developments will be discussed in Chapter 25.

Significance of Meiosis. Meiosis quite obviously constitutes a mechanism whereby haploid reproductive cells are formed from diploid progenitors. During the two divisions of the original cell, only one division of the chromosomes occurs. Consequently, meiosis inevitably produces a *reduction* in the chromosome number. Meiosis and fertilization together constitute a sys-

tem by which half the chromosomes of the new individual are derived from each of the parents, without at the same time leading to a progressive increase in the chromosome number of the species. In conjunction with fertilization, meiosis provides a basis for sexual reproduction—permitting the evolution of bi-parental inheritance. Bi-parental inheritance in turn greatly increases variability in the inherited qualities of the species. In species where the only method of cell multiplication is mitosis, the reproductive processes must remain asexual; and in view of the fact that the chromosomes passed on to the ensuing generations are quite identical with those of the parent, hereditary variability in asexual forms remains at a minimum.

Reproduction in Simpler Organisms. Strictly speaking, the term reproduction is restricted to processes whereby *total* new organisms are generated by their respective parents. Thus the mere multiplication of cells in a multicellular organism does not of itself constitute reproduction. Only when the single cell is at the same time a complete organism, as in the Protozoa and other unicellular forms, does it happen that cell division alone constitutes a form of reproduction.

The reproduction of an organism may be *sexual* or *asexual*, depending upon whether or not *fertilization* comes into play. All forms of reproduction which involve fertilization are designated as sexual, whereas all reproductive processes not involving fertilization are, by this token, asexual.

Asexual Forms of Reproduction. 1. *Binary fission.* This term is employed when an organism divides directly into two approximately equal parts, each of which then grows into an individual similar to the departed parent. The commonest form of binary fission results when a unicellular organism undergoes mitosis (Fig. 29). However, there are some multicellular forms, like certain flatworms, which reproduce by splitting directly into two quite equal pieces (p. 509).

Among Protozoa, bacteria and algae, the two cells formed by binary fission *usually* separate soon after division, swimming or crawling away, each on its separate mission. Consequently such species remain strictly unicellular. But the cells of some non-

motile forms adhere together throughout several divisions. Thus they form *incipient colonies* of loose and indefinite form. Such colonies disintegrate readily with mechanical disturbances such as currents in the surrounding water. The formation of definite colonies depends upon a more firmly established tendency of cells to cling together through a series of divisions; and in a *true colony* the planes of division, and consequently the arrangement of the cells, become fixed and regular. In a linear colony such as Spirogyra, for example, all cell divisions occur at right angles to the length of the filament, and the cells remain fastened together end to end (Fig. 20). Such colonies cannot be dispersed except by rather violent disturbances, or by the death and disintegration of some of the cells in the chain. Many cell aggregates, even such definite colonies as Spirogyra, display no real distinction between the reproduction of the individual cells (cell division) and the reproduction of the whole colony. Only after further evolution—with the development of special cells which assume the reproductive function of the colony or organism—does this distinction become very plain.

Although binary fission is probably the oldest and most primitive kind of reproduction, it is not restricted entirely to unicellular forms. A few multicellular animals such as Hydra (Fig. 34) and Planaria (Fig. 177) can also reproduce by fission. When a multicellular organism splits into two quite equal parts, each part then grows into a new individual. And even such highly organized creatures as earthworms can behave in similar fashion, if *cut* into two pieces of fairly equal size.

2. *Budding*. This asexual form of reproduction is similar to binary fission, except that the two parts into which the body divides are conspicuously unequal. A most familiar example of budding is exhibited by dividing yeast cells (Fig. 68). Here it is seen that one of the daughter cells receives only a minor share of the cytoplasm, although the nucleus of the smaller is equal to that of the larger daughter cell. The smaller daughter cell, called the *bud*, thus retains a full potentiality for growth and activity. In time the bud may catch up with its larger sister, which meanwhile may continue to give off other buds. In an

undisturbed medium the yeast cells may cling together for several generations and thus give the appearance of a small branching filament. However, their attachments are tenuous, and *definite colonies* are not formed in this particular kind of plant.

Budding is fairly common among the Protozoa, and it occurs also in some multicellular plants and animals. But in the latter case the bud is not a single cell, but an aggregate of cells derived by mitosis from the cells of the parent. In Hydra, for example, the bud develops into a small but complete new individual before it becomes detached and independent (Fig. 34).

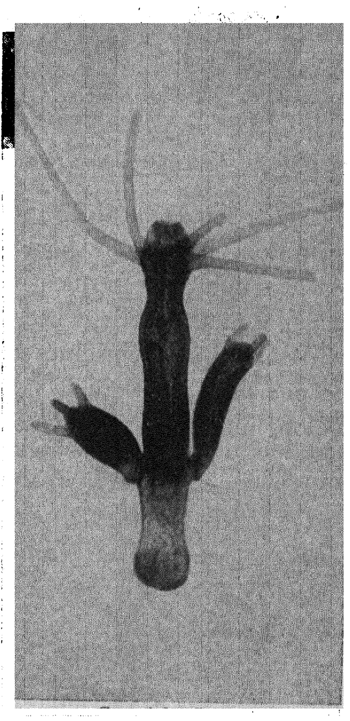


FIG. 34.—Parent Hydra, with two buds.

3. *Sporulation.* The formation of *reproductive spores* is very common among simpler organisms, and practically universal among higher plants. Typically each spore forming cell undergoes two or more divisions, producing four or more *spores.* The spore, unlike an egg or sperm, develops into a new individual *without any process of fertilization.* The sporulation divisions usually occur inside the cell wall of the spore mother cell (Fig. 35); and usually each spore develops its own tough casing, making it quite resistant to dry conditions. Certain yeasts reproduce not only by budding but also by sporulation. When the medium in which the yeasts live begins to dry up, or becomes otherwise unsuitable for life, each of the cells divides into four equal spores, possessing individual protective covers, but all contained within the original cell wall (Fig. 35). Later this outer casing ruptures and the liberated spores may be blown about

in the dry atmosphere without suffering death from loss of water. Finally the spore may chance upon a suitable new medium, where it may begin to grow and bud again.

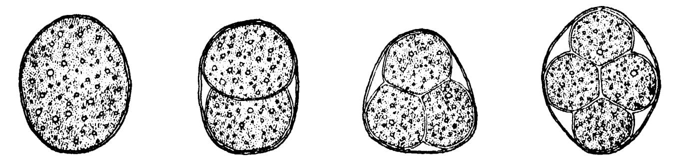


FIG. 35.—Spore formation in yeast cells (unstained).

Many species of algae reproduce asexually by means of free-swimming flagellated spores, called *swarm-spores*, or *zoospores*. At least four, but frequently many, zoospores are formed from a single mother cell, as in Ulothrix (Fig. 36). In this plant the zoospores free themselves and start migrating in all directions. If one finds a favorable new location, it settles down and develops into the ordinary attached (sessile) form of the plant.

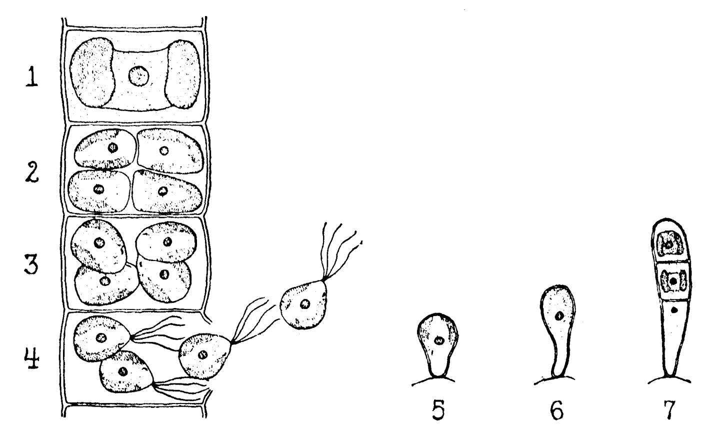


FIG. 36.—Sporulation in Ulothrix, a green alga. 1, cell of the filament before reproduction starts, showing the small round nucleus, flanked by the single large chloroplast; 2-4, formation and liberation of the zoospores; 5-7, development of a zoospore into a new filament.

Among the higher plants, including the mosses, ferns and seed plants, asexual reproduction by means of sporulation occurs at regularly alternating periods during the life cycle of each

species. In these plants the number of spores produced by each of the *spore mother cells* has become reduced to a *standard of four*. Each spore mother cell divides only twice to produce its quota of spores. These two divisions are *meiotic* in character, and consequently the *spores in all higher plants are haploid cells*. Each spore develops *without fertilization* into a form of the plant in which all the cells are haploid. Only later in the cycle, do such plants produce eggs and sperm. Then fertilization occurs and the diploid condition is restored (see Chap. 11).

Sexual Reproduction. Bacteria and blue-green algae, which are very primitive plants, reproduce entirely by asexual methods. But a great majority of living things, including many unicellular and colonial forms, exhibit sexual reproduction. In these cases, fertilization always occurs in one form or another.

The essential feature of fertilization is the fusion of two haploid nuclei which usually are recognizable as the egg nucleus and the sperm nucleus. Ordinarily the resulting diploid nucleus becomes the progenitor of all the nuclei of the new individual. In more primitive forms, however, it is not always possible to distinguish between the egg and sperm cells. Sometimes the two cells which undergo fusion appear to be quite identical, and therefore it is necessary to speak in broader terms. The two haploid cells which come together in fertilization, whether similar or dissimilar in appearance, are always designated as the *gamete* cells. The egg, when distinguishable, is called the *female gamete*, and the sperm, the *male gamete*. Furthermore, the diploid nucleus created by the fusion of the gamete nuclei, is always called the *zygote nucleus*; and the whole cell formed at the time of fertilization is the *zygote*. In evolution apparently sexual reproduction came before any differences had developed in the external appearance of individuals of opposite sex, or between the gametes produced by the two cooperating parents.

Isogamy vs. Heterogamy. A number of examples can be found which illustrate the foregoing principles. In Spirogyra and closely related species, the ordinary cells of the filament are haploid cells; and any or all of these filament cells may act

as gametes. When Spirogyra engages in sexual reproduction—and this usually occurs in the fall of the year—the pairs of cells which happen to lie oppositely on two nearby filaments, begin to show signs of mutual stimulation. Short tube-like processes grow out from each of the prospective gametes (Fig. 37). These outgrowths join in pairs, and the cell walls dissolve away at

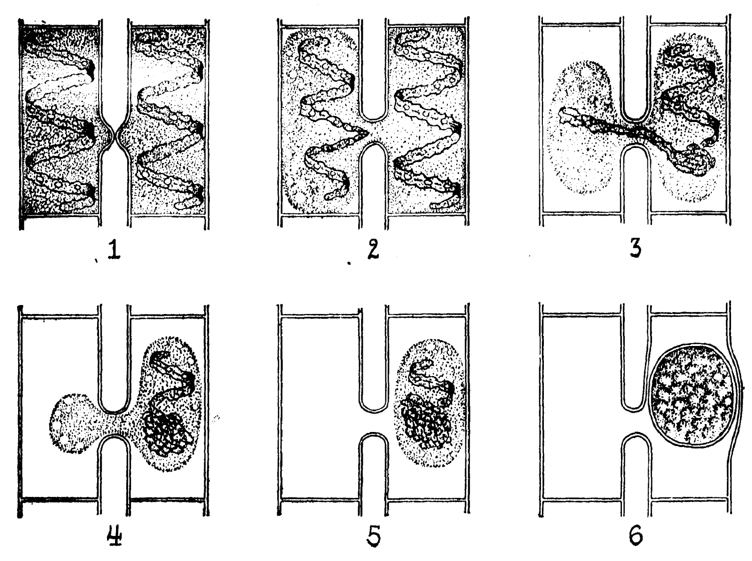


Fig. 37.—Conjugation of Spirogyra (see text).

the points of contact. In this way an open tube is formed connecting the members of each pair of conjugating cells (Fig. 37). Soon all the protoplasm of one gamete passes through the *conjugation tube* and fuses with the protoplasm of the other. Finally—and this is the essence of fertilization—*the two haploid gamete nuclei fuse to form the diploid zygote nucleus.*

In the case of Spirogyra the gamete cells are identical in appearance. Accordingly these gametes are specified as *isogametes,* and the production of such gametes is called *isogamy.* Conversely, cases where the gametes (*heterogametes*) are obviously not alike are designated as *heterogamy.* Although isogamy is fairly widespread among primitive organisms, it is not encountered in higher forms. Heterogamy became dominant early

in evolution, and fully differentiated eggs and sperm are common to practically all multicellular animals and plants.

Shortly after fertilization the zygote of Spirogyra develops a very thick cell wall and becomes a resting cell, called the

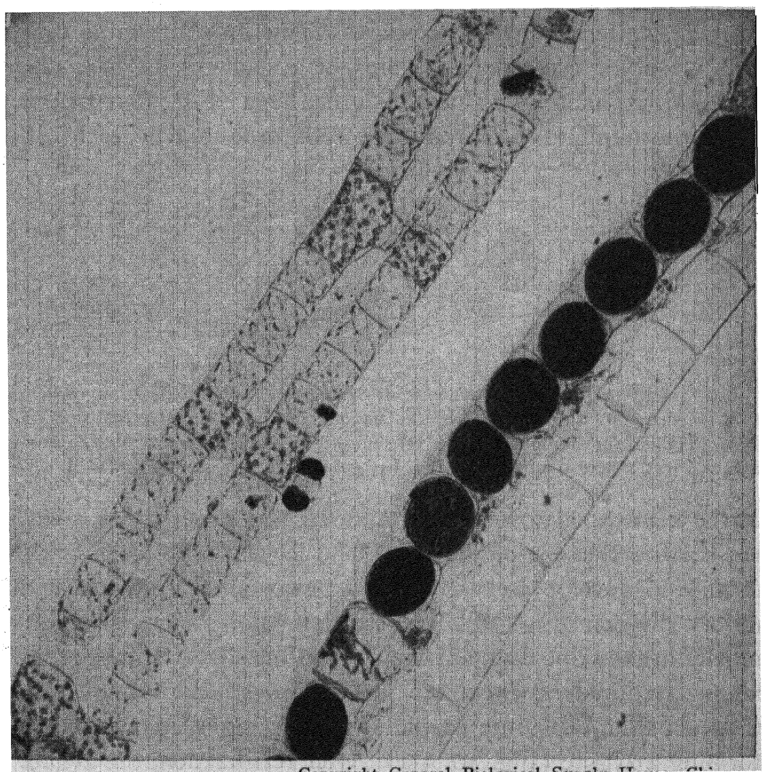


FIG. 38.—Photo of conjugating Spirogyra. The upper pair of filaments shows two pairs of cells at the outset of conjugation; and the lower filaments show several zygospores (dark oval bodies) which result from conjugation.

zygospore (Fig. 38). The zygospore is resistant to freezing, and able to survive through the winter. Then in the spring, the zygospore germinates (Fig. 39); but just before a new filament is formed, the zygote nucleus divides twice in rapid succession. In Spirogyra, *these are the meiotic divisions*. Four haploid nuclei are thus produced, but three of these degenerate prior to germination (Fig. 39). The remaining haploid nucleus gives

rise by mitosis to all the nuclei of the new filament, and consequently all the cells of the colony are haploid cells.

Isogamy is also encountered in many other algae, and in a few fungi and Protozoa. Most higher algae, however, have specialized gametes, which are small flagellated cells, similar to, but smaller than, the zoospores. Sometimes the same cells may act either as asexual zoospores, or as gametes, as is the case of Ulothrix, another filamentous green alga (Fig. 36). In this plant the number of reproductive cells produced by each cell

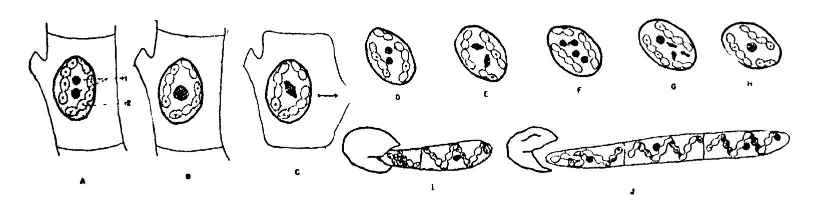


FIG. 39.—Fertilization and meiosis in Spirogyra. A-B, fertilization (which usually occurs in the fall); C-F, the meiotic divisions; G, degeneration of three of the four haploid nuclei; I-J, mitotic multiplication of the haploid cell to form a new filament of cells. (1, gamete nuclei, 2, chloroplast.)

of the filament may vary from 4 to 64; the larger the number, the smaller the size of the cells. The larger spores soon settle down and develop asexually into a new filament, by repeated mitotic division (Fig. 36). The smaller "spores" may also germinate in the same way, but their growth is slower and the filaments produced by them are less vigorous. More frequently these smaller cells fuse in pairs, thus acting as gametes and forming a zygote (Fig. 40, 3-4). After fertilization, the zygote develops into a thick-walled zygospore, as in Spirogyra. Likewise in Ulothrix, the diploid zygote undergoes two divisions, the *meiotic divisions*, just before germination. At first the four resulting haploid cells lie huddled together inside the old cell wall (Fig. 40, 6); but finally, after this encasement has disintegrated, each of the four haploid cells gives rise by mitosis to a separate new filament.

The evolutionary transition between isogamy, which is very common among simpler organisms, and heterogamy, which reaches a standardized condition in the eggs and sperm of

higher plants and animals, can be found in a single family of free-swimming green algous plants. This family, the Volvocaceae, is made up of many species, but only three species will be mentioned in the present connection.

All of the Volvocaceae reproduce both sexually and asexually. The gametes formed by *Pandorina* (Fig. 41, B) are of two sorts, one slightly larger than the other. When fertilization takes place, one of the smaller. or *microgametes*, usually fuses

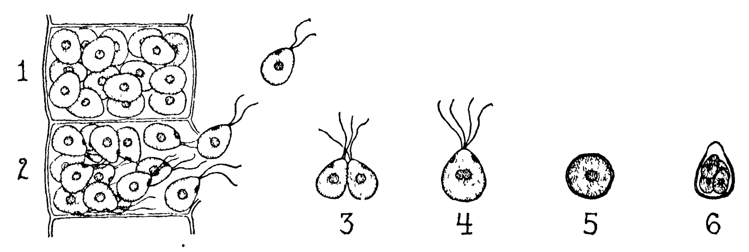


FIG. 40.—Sexual reproduction of Ulothrix. 1, 2, formation and liberation of gametes, 3, 4, conjugation of gametes; 5, zygote, 6, division of zygote into four spores, each of which develops into a new filament (as shown in Fig. 36).

with a larger, *macrogamete*. But sometimes two microgametes, or two macrogametes, will come together. In either case, a diploid zygote is formed, and this gives rise to the new colony. Accordingly it may be said that Pandorina shows the first beginnings of a difference between the gametes of the sexes.

In Eudorina (Fig. 41, C) and Volvox (Fig. 41, D), the differentiation between the gametes has developed much further. The macrogametes of Eudorina are several times larger than the microgametes—although both gametes are flagellated and motile. Moreover, fertilization always involves a fusion of the *unequal* gametes. But the climax of heterogamy is reached in Volvox (Fig. 42, E). The macrogamete of Volvox, due to its relatively large size and its inability to move, can properly be called an egg; and the very small *motile* microgamete is truly a *sperm*.

The differentiation between the sperm, which is small and motile, and the egg, which is large and non-motile, represents

an efficient division of labor. The size and motility of the sperm-cell makes it an effective agent for carrying the paternal chromosomes to the zygote. Usually the sperm are produced in very

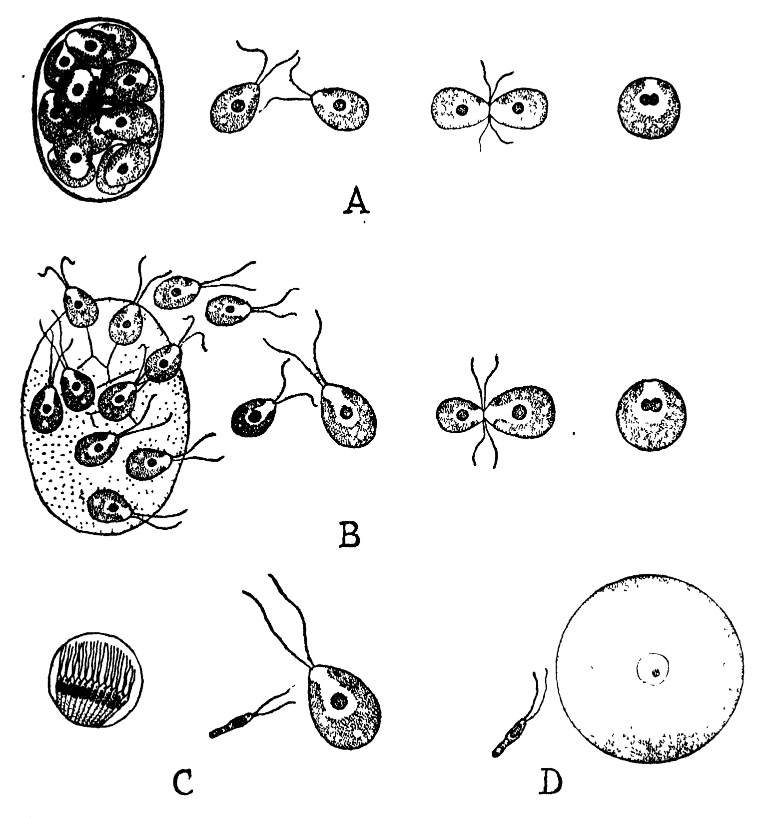


FIG. 41.—Sexual reproduction of several Volvocaceae. A, Chlamydomonas; formation of gametes and conjugation of two equal gametes. B, Pandorina; liberation of gametes and conjugation of two unequal gametes. C, Eudorina; formation of gametes; a micro- and a macrogamete. D, Volvox; a microgamete (sperm cell) and a macrogamete (egg cell).

large numbers and discharged near the eggs. Consequently at least one sperm is almost sure to find and penetrate each egg. The egg cell, on the other hand, is adapted for the reception of the sperm and for assembling the maternal and paternal chromosomes to form the zygote nucleus, which will give rise to all the nuclei of the offspring. Also the egg is laden with

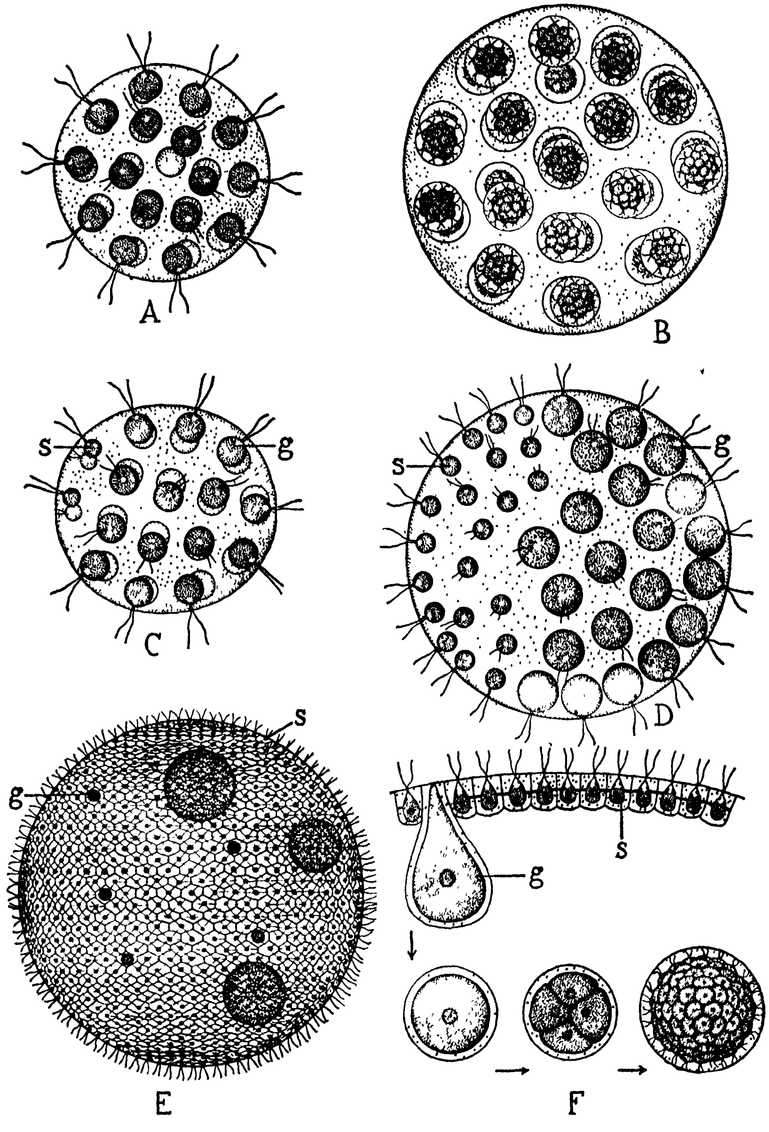


FIG. 42.—Several colonial Volvocaceae. A, Eudorina; B, the same with young colonies developing by division of the cells of the old colony; in this genus every cell is a germ cell. C, Pleodorina illinoisensis; D, Pleodorina californica. E, Volvox, whole colony, with young colonies developing inside the old one; F, small portion of the colony, more highly magnified, showing the development of germ cell into new colony. s, somatic cells; g, germ cells.

yolk and other stored material to nourish the offspring during its embryonic development, i.e., until the new organism is capable of obtaining food for itself. And since eggs and sperm are the agency for sexual reproduction in a large majority of plants and animals, there can be little doubt as to the efficiency of these developments.

Life Cycles: Haploid and Diploid Phases. The complete life span of an organism, starting at any given stage, and extending to the time when the offspring reach the same stage, constitutes the *life cycle* in each species. In some species, the life cycle is very simple, but in others it is quite complex.

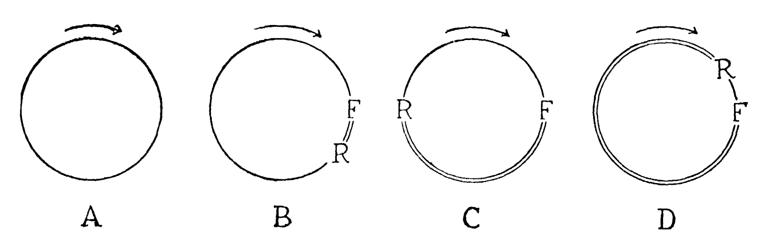


FIG. 43.—Diagrams illustrating the relations of the haploid and diploid stages in various types of life cycles (see text). In each figure the single line represents the haploid, the double line the diploid, condition. The direction of the arrows indicates the succession of cell generations. F, fertilization; R, reduction. A, type of "cycle" found in asexual organisms (e.g., Bacteria); B, type of cycle found in Spirogyra and many other green algae; C, cycle of higher plants; D, cycle of higher animals.

The Amoeba and other organisms that reproduce solely by binary fission, display the very simplest type of life cycle. The young Amoeba feeds, grows, and then divides, which returns the species directly to the starting point. Such a cycle is devoid of any sexual stages, and consequently the terms diploid and haploid have no real meaning. Without fertilization no diploid stage is ever formed, and it is only by arbitrary convention that the cells in such species are regarded as haploid (Fig. 43, A).

Another type of life cycle, which characterizes many green algae, is exhibited by Spirogyra. During the *major part* of the life cycle, while the colony is multiplying asexually by mitosis, the cells remain *haploid*. The diploid stage starts at the time

of fertilization and persists only until meiosis occurs. This is in the spring, just before the zygospore germinates to form a new filament, which again is haploid (Fig. 43, B).

The opposite type of cycle is found in almost all multicellular animals, including man, and in a few primitive plants. In man, the diploid stage begins when the egg is fertilized, and persists in all the body cells, which arise from the fertilized egg by mitosis. Meiosis occurs very late in the cycle, when the eggs and sperm are being produced in the sex organs. This type of cycle is shown in Fig. 43, D.

The final type of cycle, which is intermediate between the preceding two, is found in all higher plants (Chap. 11), and in a few multicellular algae. In this type of cycle (Fig. 42, C), there is a regular alternation of haploid and diploid generations. The fertilized egg always gives rise to a diploid plant body which reproduces asexually—by forming spores. This diploid asexual generation in higher plants is therefore called the *sporophyte generation.* The spores in all higher plants are produced by meiosis in groups of four from the spore mother cells in the spore capsule. Consequently the spores are always haploid. Each haploid spore invariably gives rise to a haploid form of the plant, which eventually will reproduce by gametes. Thus the haploid sexual generation in higher plants is called the *gametophyte.* Finally when fertilization again takes place, the diploid condition of the succeeding sporophyte generation is restored, and the cycle is completed.

The early evolution of reproductive structures among plants and animals occurred by trial and error. A variety of methods first appeared among primitive organisms; but only a few were successful enough to be passed on to higher plants and animals.

TEST QUESTIONS

1. Explain three important differences and three important similarities between *mitosis* and *meiosis.*
2. What is *amitosis?* Why is amitosis *not* regarded as a *normal* kind of cell division?

3. In proper sequence list the events which occur during the prophase of mitosis: (a) in a plant cell; (b) in an animal cell.
4. How does the prophase of the *first* meiotic division differ from the prophase of mitosis?
5. How are metaphases and anaphases to be distinguished from the other stages of mitosis?
6. In mitosis, what invariable rule determines the movements of the members of each pair of daughter chromosomes (the two chromosomes formed by the splitting of each parent chromosome)?
7. What importance is attached to the fact that each chromosome divides *lengthwise*, rather than *crosswise*?
8. Specify two ways in which the *telophases* of plant and animal cells are: (a) different; and (b) similar.
9. Assuming that the chromosomes were distinctly visible, how would you decide whether a given cell were *haploid* or *diploid*?
10. Explain the term *homologous chromosomes*.
11. Is it true that any species of plant or animal can be identified by studying the chromosomes of one of its cells? Explain your answer carefully.
12. In man's body, most of the cells are formed by mitosis, but some are produced by meiosis. Explain this statement more specifically.
13. Identify each of the following terms: (a) spireme chromosomes; (b) spermatogonia; (c) primary spermatocytes; (d) synapsis; (e) tetrads; (f) secondary spermatocytes; (g) diads; (h) spermatids; (i) sperm.
14. In each case specify the distinguishing features and cite a specific example: (a) asexual reproduction; (b) binary fission; (c) budding; (d) sporulation; (e) zoospores.
15. Carefully define each term and in each case cite *three* specific examples: (a) a gamete cell; (b) the zygote; (c) fertilization.
16. Distinguish between isogamy and heterogamy; cite two examples in each case.
17. Divide the following cells into two lists according to whether they are haploid or diploid: (a) fertilized eggs; (b) the tissue cells of man's body; (c) sperm cells; (d) unfertilized eggs; (e) the zygospore of Spirogyra; (f) the zygospore of Ulothrix; (g) the macrogamete of Pandorina; (h) a spore mother cell; (i) the spore of a higher plant.

18. In the life cycle of each of the following organisms, specify where fertilization and meiosis take place: (a) man; (b) Spirogyra; (c) any higher plant; (d) Amoeba.
19. Carefully explain each of the following statements: (a) certain features of mitosis very plainly indicate that among the various structures of a cell the chromosomes are of paramount importance; (b) jointly, meiosis and fertilization provide a basis for *bi-parental* inheritance.

FURTHER READINGS

1. *The Riddle of Cancer*, by Charles Oberling (translated by William H. Woglom); New Haven, 1944.
2. *The Biology of the Cell Surface*, by E. E. Just; Philadelphia, 1939.
3. *Experimental Cytology*, by James Gray; London, 1936.

CHAPTER 4

THE CHEMICAL AND PHYSICAL STRUCTURE OF PROTOPLASM

THE MICROSCOPE provides many clues as to the functions of the different parts of the cell. But below the reach of the microscope there lies a realm of smaller things: the world of molecules and atoms, which compose the ultimate structure of all matter. Biologists now realize that the visible parts of the cell are very important; but full attention must also be given the sub-microscopic *molecular pattern* of protoplasm. This means that an irreducible minimum of biochemistry and biophysics has become basic in general biology. The cell, essentially, is a delicate physico-chemical mechanism; and the merest trace of a foreign chemical such as cyanide, or the slightest excess of a physical factor such as heat, may derange the finely poised molecular structure of the protoplasm, killing the cell immediately.

Each cell faces the problem of obtaining a quantity and variety of substances sufficient to *maintain* and *operate* its existing protoplasmic structure, as well as to increase the protoplasm when *growth* occurs. But before the chemistry of growth, maintenance, and operation can be considered, it is necessary to know the general composition of living matter. What substances are always present? How much of each of these essential components must there be? And how are these active molecules assembled and arranged with reference to visible structures in the cell?

No two samples of protoplasm are ever *precisely* identical; but the many differences found among various cells are mainly

matters of detail. One cell utilizes a certain kind of sugar which differs slightly from the sugar used by another. Plant cells synthesize starch; whereas animal cells build glycogen, a closely related compound. But above and beyond these specific variations, there is a general pattern, and all protoplasm conforms to this pattern. Always the same types of chemical compounds are present, and these compounds play similar roles in the protoplasm of plants and animals generally.

Merely to list the specific compounds which can be extracted from the cell would be a difficult task. The list, in fact, would take on the proportions of a telephone directory. A far simpler approach is to ascertain the *elements* out of which these many compounds are formed. What various *atoms*, combined together to form a great variety of molecules, are present in the protoplasm? Assuming that a sample of protoplasm were placed in a sealed retort and subjected to such drastic chemical treatment that each of the many compound molecules were decomposed into its elements, *what atoms would be yielded?*

Elementary Constituents in Protoplasm. Table I shows that oxygen, hydrogen, carbon and nitrogen account for a very large proportion of the weight of the protoplasmic compounds. These same elements are also most abundant in the non-living materials of our world. Among the 92 elements which compose all matter, carbon, hydrogen, oxygen and nitrogen are uniquely fitted for their functions in the protoplasmic system. So far as we know living things have not arisen on other planets where these elements are less abundant—and this is probably not a matter of coincidence.

Among the 92 elements, only those given in the list are generally found in protoplasm, although a few others are found in special cases. All the protoplasmic elements are very common in non-living nature, being abundantly represented in the soil, the atmosphere and the waters of the earth. No single element is entirely peculiar to living things. However, a few—especially carbon and nitrogen—are relatively much more abundant in living than in non-living matter.

TABLE I

ELEMENTS LIBERATED BY DECOMPOSITION OF PROTOPLASMIC COMPOUNDS

Name and Symbol	*Average Percentage by Weight*	*Combining Capacity (Valence)*	*Common Appearance, as the Free Element*
Oxygen (O)	76.0	2	Colorless gas; supports combustion; 16× heavier than hydrogen
Hydrogen (H)	10.0	1	Very light inflammable gas; comparative weight = unity
Nitrogen (N)	2.5	3 and 5	Colorless non-inflammable gas; 14× heavier than hydrogen
Carbon (C)	10.5	4	Black solid
Sulfur (S)	.2	2 and 6	Yellow solid
Phosphorus (P)	.3	5	Red solid
Potassium (K)	.3	1	Light metallic solid
Iron (Fe)	.01	2 and 3	Heavy metallic solid
Magnesium (Mg)	.02	2	Light inflammable metal
Calcium (Ca)	.02	2	Light metal
Sodium (Na)	.04	1	Light active metal
Chlorine (Cl)	.10	1	Heavy greenish gas
Copper (Cu)	Trace	1 and 2	Metallic solids
Cobalt (Co)	Trace	2 and 3	
Zinc (Zn)	Trace	2	
Manganese (Mn)	Trace	4	

BASIC IDEAS AND DEFINITIONS[1]

Matter and Energy. The material component of our universe—*matter in general*—is to be identified by its universal properties. Always *matter* occupies space, and always it displays *weight*. Each kind of matter may assume the form of a *solid* (like ice), or of a *liquid* (like water), or of a *gas* (like water vapor); but whatever its form, matter always retains its identifying attributes.

[1] Two kinds of type are used in this section of the book. For students who have not had chemistry previously, the material in smaller type is just as important, if not more important, than the material in larger type. For students who have had chemistry, the material in smaller type will be useful as a review.

Energy is the other fundamental component of our universe. Energy may take a variety of forms, such as light, heat, mechanical movement, electricity, and so forth. In fact energy can only be identified in terms of what it *does*, or what it *can do*. *Energy is the motion of, or the capacity to produce motion in, any mass of matter.* Sometimes the energized mass is very small, as in the case of the flowing electrons of an electric current, or the vibrating molecules of a heated substance; or the material body may be larger—like a bullet hurtling from the barrel of a rifle.

All forms of energy are at least partially interconvertible (Table II) as can be illustrated by the electric system of an automobile. The

TABLE II

FORMS OF ENERGY

	Kinetic	*Potential*
Polymolecular *	Movement (mechanical energy)	Weight (gravity)
Molecular	Heat	Cohesion and adhesion †
Atomic	Chemical reaction	Chemical reactivity
Electronic	Electric current	Electric charge
Radiant	Light, X-rays, etc.	

* Pertaining to masses of visible size.

† Cohesion is attraction between molecules of the same substance; adhesion is attraction between molecules of different substances.

battery of the car contains a store of *chemical energy* represented by the reactivity of the acid and other chemicals of the battery. This chemical energy is transformed to *electrical energy* whenever the headlight switch is closed; and as the electricity flows through the filament of the lamp bulb, electrical energy is converted to *heat*. Then when the temperature of the lamp filament reaches the incandescent point, the heat begins to be transformed into *light*. Or if the starter switch is pushed and the electricity flows through the starting motor, electrical energy is converted into *mechanical energy* (the movement of the pistons, etc.) as the engine is forced to "turn over" before it "catches."

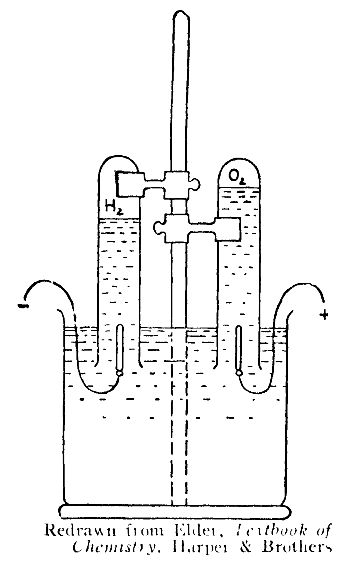
In modern science, everything that happens—every natural event and phenomenon—is to be explained and described in terms of matter and energy; in terms of some change, actual or potential, in the internal or external motion of the components of some material system. Throughout the universe, matter and energy are inseparably associated. Each acts and interacts solely through the medium of the other. Attempting to understand the general principles of biology, chemistry or physics, without reference to matter and energy, would be like trying to appreciate the beauty of a landscape in a world devoid of light.

Molecular Composition of Matter. Each mass of matter, regardless of its specific kind, is composed of a great number of subvisible unit particles, the *molecules*. This knowledge has become so commonplace that many students do not pause to question its origin, although there is a large body of experimental evidence from every field of science which firmly establishes the molecular nature of matter.

Let us choose any sample of *matter*, such as water. As everyone knows, water *exists in three states:* as a *solid* (at temperatures below the freezing point, 0° C.), as a *liquid* (at temperatures between 0° and 100° C.), and as a *gas* (above 100° C.). In the gaseous state, of course, the water is not visible. As soon as the water molecules, which in the solid and liquid states are quite closely packed into a tangible mass, have absorbed enough heat energy to escape as individuals from the common mass, their subvisible smallness is revealed. But water was chosen at random to exemplify matter generally. All other samples of matter—all other *specific chemical substances*—can undergo similar *changes* of state, although in some cases the practical conditions are hard to realize. In the *solid state* the molecules of a substance are relatively closely packed and the intermolecular attractions are strong enough to prevent the free migration of the individual molecules within the solid mass, although each is free to vibrate (due to heat energy) in the region of a relatively fixed locus. In the *liquid state* the intermolecular distances are greater and consequently the forces of attraction between the molecules are significantly smaller. Under these conditions, the individual molecules are free, not only to vibrate, but also to migrate (more and more rapidly as the absorbed heat energy increases) through the body of the liquid, although they are not free to escape *en masse* from the definitive boundary of the liquid. Finally, when a liquid has been energized by heat

beyond a certain critical point, the molecules of the mass separate themselves more or less completely from the intermolecular attractions; and in the *gaseous state*, the subvisible smallness of the individual molecules becomes apparent.

Molecules vs. Atoms. There are thousands of different kinds of matter, such as water, sugar, oxygen, nitrogen, etc., or—as the chemist expresses it—thousands of specifically different *substances*, each characterized by a different kind of molecule. The problem of identifying these many specific molecules belongs, of course, to the field of chemistry. But the molecules present in protoplasm also belong to biology; and it so happens that some of the protoplasmic molecules are extremely complex as to their chemical structure.



Redrawn from Elder, *Textbook of Chemistry*, Harper & Brothers

FIG. 44.—When a direct current flows through water, the water molecules decompose into hydrogen (left test tube) and oxygen (right test tube).

The chemist designates each specific molecule by its *formula*, which specifies the atoms which are combined in definite proportion in each different molecule—as, for example: water = H_2O; table sugar = $C_{12}H_{22}O_{11}$; and oxygen = O_2. If such examples were repeated indefinitely, it would be found that the molecular formulae of all known substances can be given by using the symbols of only 92 different atoms (elements). In other words, the same 92 elementary atoms enter into a multitude of specific chemical combinations in forming the molecules of all substances in our universe.

The methods used by the chemist in determining that a sugar molecule is to be designated as $C_{12}H_{22}O_{11}$, or the water molecule, as H_2O, are difficult and indirect; but taken as a whole, they are absolutely convincing. However, only the slightest indication of these methods can be given here.

In the case of sugar, it is not difficult to demonstrate that carbon (C) is present in the molecule. Anyone who has heated sugar and allowed it to *char* has demonstrated this point. At high tempera-

ture sugar molecules begin to decompose, liberating carbon, the familiar black solid, which is easily recognized. The presence of hydrogen (H) and oxygen (O) in the sugar molecules can also be demonstrated by heat decomposition, carried on in a sealed retort. Under these conditions, the water (H_2O) which is liberated, can be collected and identified. And finally, the water can be decomposed by

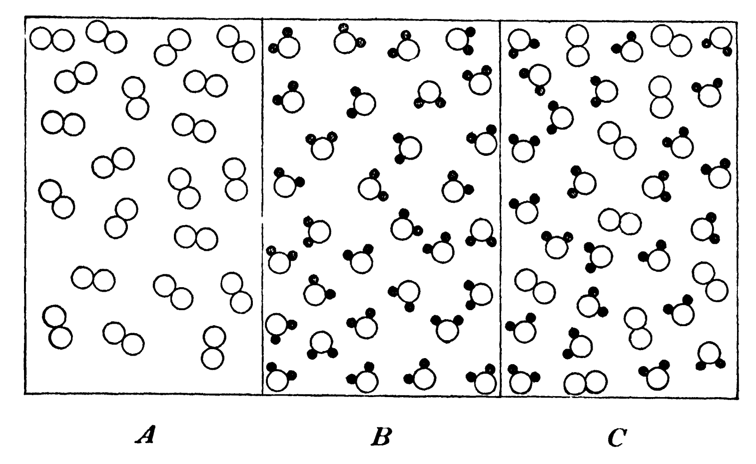


Fig. 45.—Diagrams representing two substances (A and B), and a mixture (C). The large open circles represent oxygen atoms, the smaller dark circles hydrogen atoms. A, a free element, oxygen (O_2); all the molecules are alike and contain only one kind of atoms. B, a compound, water (H_2O); all the molecules are alike, each consisting of one oxygen and two hydrogen atoms. C, a mixture of water and free oxygen (i.e., oxygen dissolved in water), which may be mixed in various proportions.

means of a strong direct current, and the liberated hydrogen and oxygen can be identified (Fig. 44).

The molecules of a substance are the smallest unit particles of that substance; and if a substance be subdivided into particles smaller than its molecules, it no longer remains the same substance. Water, for example, becomes hydrogen and oxygen; or sugar becomes carbon, hydrogen, and oxygen. *Atoms,* on the other hand, *are the 92 kinds of smaller particles which combine together in fixed proportion to form a countless variety of molecules.*

Substances vs. Mixtures. Every sample of matter is either a *substance* or a *mixture* (Fig. 45). Strictly speaking, a *substance is a purified single kind of matter in which all the molecules are of the same species.* Purified (distilled) water, or highly refined sugar,

or pure oxygen, must therefore be designated as substances. *Mixtures, unlike substances, are made up of more than one kind of molecule.* Pond water, although it is composed chiefly of H_2O molecules, also contains molecules of various minerals, as well as the molecules of dissolved air; or air contains molecules of oxygen, nitrogen and small amounts of other gases; and consequently these latter kinds of matter are designated as mixtures.

In practice one can distinguish a substance from a mixture containing that substance in large proportion by the fact that the purified substance displays a non-variable and standard set of physical and chemical properties. Each specific substance can be identified with absolute certainty by its known properties. A purified sample of water (H_2O) displays the same properties regardless of whether it is obtained from Siberia or Afghanistan. Its physical properties (color, taste, odor, boiling point, freezing point, etc.), and its chemical properties (see later), allow no question as to its identity as a single substance; and the same holds true for all other known substances. Table sugar, or more properly *sucrose*, $C_{12}H_{22}O_{11}$, can be distinguished from all other similar and dissimilar substances, on the basis of exact measurements of its melting point, crystalline structure, degree of sweetness, solubility, and other of its specific physical and chemical attributes.

A *mixture*, in contrast to a substance, *displays variable properties*, depending upon the proportions of the mixed components. The properties of pond water, for example, vary widely according to the locality from which it is collected. It may contain different mineral salts from the soil and various amounts of the atmospheric gases. It may display a wide variety of tastes and colors and considerable variation in the boiling and freezing points. It may even be toxic when drunk. Or crude sugar may be light or dark, strongly or weakly sweet, easy or difficult to dissolve, and so forth—depending upon the refinement of the methods used to extract it from the cane. The variations of a mixture depend upon the varying proportions of the mixed substances; and perhaps the most complex and variable of all mixtures is protoplasm itself. In protoplasm the number of components is very great, and the problem of understanding their interactions is very difficult.

Chemical Combination vs. Mixing. The fixity of the properties of a substance, as compared to the variability of the properties

of a mixture, are due to the fact that *the atoms which constitute the molecules of a substance are chemically united in fixed proportion; whereas the molecules which compose a mixture may be present in any proportion.* This may be illustrated by a specific case. Take, for example, a strong gas tank containing hydrogen gas (H_2) and oxygen gas (O_2) *mixed* together (Fig. 46). In the tank the hydrogen and oxygen may be present in any proportion. With little hydrogen and much oxygen, the mixture as a whole will be relatively heavy and dense; or conversely, with little oxygen and much hydrogen, the mixture will be lighter and less dense. In other words, the properties of the mixture in the tank are altogether variable. But suppose that gradually the tank is heated. At a critical temperature combustion, which represents a chemical union between the atoms of the hydrogen (H) and the oxygen (O), will start, and then proceed with explosive speed. A fraction of a second later, all that can be recovered from within the tank is a small amount of water (H_2O) and a residual quantity of either oxygen or hydrogen—depending upon whether the exploded mixture contained an excess of the one or the other (Fig. 46). But the point to be made is that when *two or more atoms chemically unite to form a molecule, they do so in fixed proportion.* The fixed proportion which determines the specific combining power of each different kind of atom, is given by its *valence* number. Consequently this number must be learned, at least for all atoms present in the protoplasmic system (Table I).

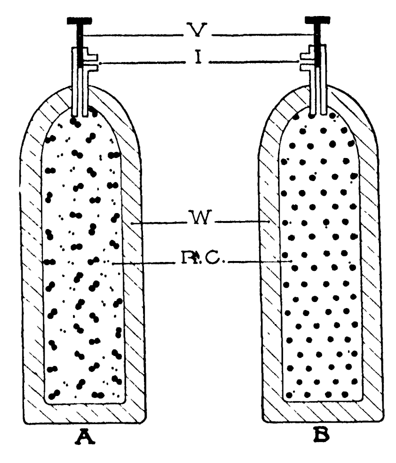


FIG. 46.—The mixing of two substances is not the same as chemical union between them. A, reaction tank contains a *mixture* of free oxygen (O_2) and hydrogen (H_2) *before* ignition has occurred. B, same tank after the hydrogen has burned (united with oxygen). Two hydrogen atoms unite with each oxygen (i.e., the atoms unite in a *fixed* proportion) so that the resulting compound, water (H_2O), is a uniform product. Large dots represent oxygen atoms; small dots, hydrogen atoms. V, valve; I, inlet tube; W, wall of reaction chamber; R.C., reaction chamber.

Atomic Structure. The fact that the molecules of all substances are constituted by specific combinations of the atoms of a limited number—now known to be 92—of different elements, has been recognized for many years. But it is only in the recent years of "atom smashing" that conclusive proof has been advanced that each atom is constituted of electrically charged smaller particles which are of just *two* sorts. The center of each atom is constituted mainly of *protons*, each bearing a single *positive* charge, although there are some negatively charged particles, the *electrons*, also present in the *atomic center.*[2] Energetically revolving around the atomic center, like the *planets* of the solar system, there is another group of electrons, the *planetary electrons.* The number of protons and electrons present in the whole configuration differs for each particular kind of atom (Fig. 47); but *always the total number of electrons present in a given atom is exactly equal to the number of its protons.* In short, each *atom, as a whole, is an uncharged body.*

A knowledge of atomic structure provides an understanding of how various atoms enter into chemical union. One group of the atoms (the *electro-positive atoms*) tends to give up one or more *planetary electrons*, transferring the electrons to the planets of atoms of another group (the *electro-negative atoms*), which have a tendency to gain planetary electrons. When such an exchange occurs (Fig. 48), the participating atoms tend to cling together, constituting a molecule. The atom which has lost electrons now possesses a positive charge, and this makes it cling to the other atom, which having gained electrons, possesses a negative charge. Such studies also explain the existence of a third general group of atoms, the *inert* elements, like helium and neon (Fig. 47). These inert atoms never form any chemical compounds. Each possesses a very stable planetary system, which resists the gaining or losing of electrons. But among chemically active atoms, the number of planetary electrons which can be gained or lost during chemical union, is specified as the *valence* of the particular atom in question.

The newer knowledge of atomic physics also provides a key to other problems. It explains, for example, the source of the energy which appears or disappears whenever a chemical reaction takes place (see p. 97). Each atom is a system supercharged with energy—the *kinetic energy* of the vibrating and revolving electrons, and the *poten-*

[2] In the atomic center, each *neutron* is formed by a union between a nonplanetary electron and a proton.

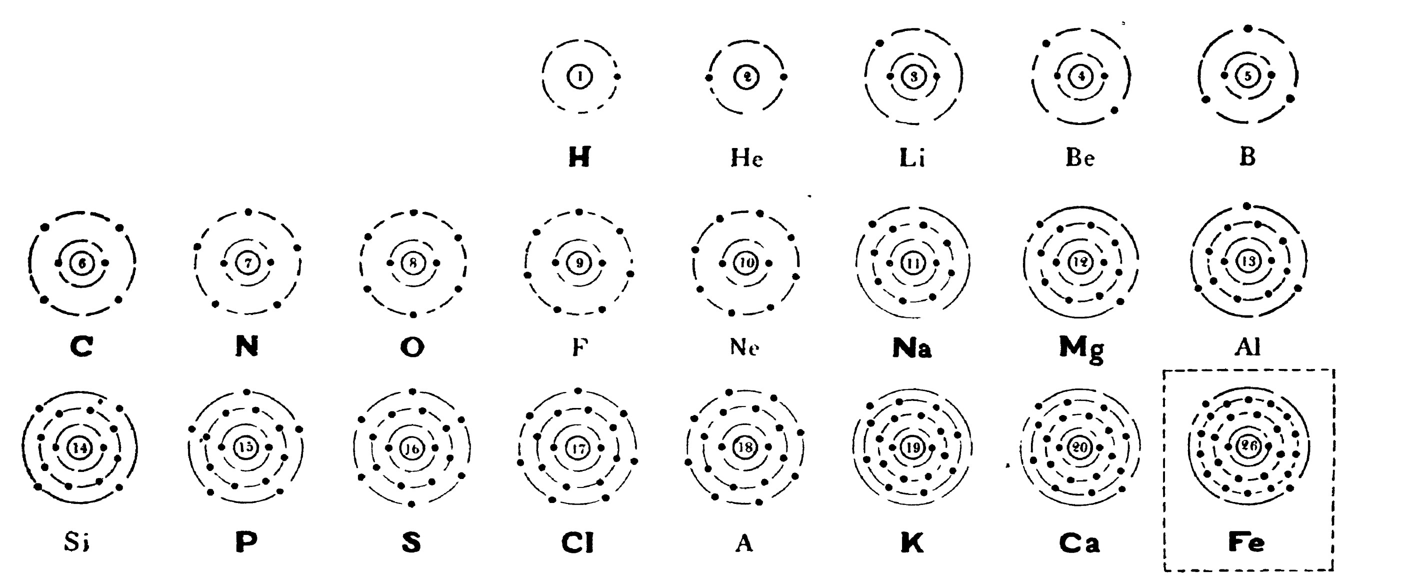


FIG. 47.—Structure of atoms of atomic numbers 1-20 and 26. The central circle represents the atomic nucleus, the number in the circle showing the net positive charge, i.e., the atomic number; the small black circles represent planetary electrons. These figures are purely diagrammatic and do not pretend to show the actual spatial configurations of the electrons. The atoms whose symbols are printed in heavy type are those of elements generally present in living matter. H, hydrogen; He, helium, Li, lithium; Be, beryllium; B, boron; C, carbon; N, nitrogen; O, oxygen; F, fluorine; Ne, neon; Na, sodium; Mg, magnesium; Al, aluminum; Si, silicon; P, phosphorus; S, sulphur; Cl, chlorine; A, argon; K, potassium, Ca, calcium; Fe, iron.

tial energy of the electrical attractions between the protons and electrons. No two different atomic configurations ever possess precisely equal quantities of intramolecular energy. Therefore it follows that any alteration in atomic configuration, such as occurs during any chemical reaction, must involve either gain or loss of energy. Either there is an energy surplus which is put forth, or there is a deficit, which is absorbed, with reference to the environment. Accordingly, when we witness an expenditure of energy in any cell—such as the beating of cilia—we know that the energy arises from the chemical reactions which constitute the metabolism of the cell.

CHEMICAL COMPOSITION OF PROTOPLASM

Organic vs. Inorganic Substances. The many substances present in protoplasm fall naturally into two great classes, i.e., *organic* and *inorganic* substances. Early in the nineteenth century it was thought that some "vital factor" was distinctive of organic substances, because up to that time, no organic substance had ever been obtained except from the bodies of living organisms. But in 1828, Woehler first synthesized an organic compound (urea), and since then a wide variety of organic compounds have been manufactured in the laboratory—of which many, like aspirin and sulfanilamide, never existed previously. Nevertheless an important distinction remains to distinguish organic from inorganic substances. Excluding artificial synthesis, organic compounds, such as sugar, are found only in living bodies, or in their products and remains; whereas inorganic substances, such as water, are found *both* in living and in non-living bodies.

Inorganic Substances. Inorganic substances make up the bulk of living as well as non-living matter. The rocks, soil, atmosphere, and waters of the earth are composed almost entirely of a wide variety of inorganic materials. And in living matter also, the inorganic components greatly preponderate. This is due mainly to the high proportion of *water* in all protoplasm, although lesser quantities of the inorganic *salts*, *acids*, *bases*, and *gases* are likewise always present in protoplasm.

Water: Its Importance in Protoplasm. Water is by far the most abundant single compound in all protoplasm. The pro-

portion of water—in terms of the *weight* of the protoplasm—varies between 70-90 per cent in different cells; and this water is by no means inert and unimportant. Without water, there is no such thing as protoplasm; and the life-structure of any cell is immediately destroyed, if the cell loses a significant proportion of its water content.

Water is so familiar that it is difficult to appraise its functions scientifically. Nevertheless, the unique physical and chemical properties of water give it a dominant role in determining protoplasmic structure and activity. In fact, water is the chief *dispersion medium* of the protoplasm. In other words, water is the liquid which *dissolves, suspends, or otherwise disperses* most of the various other substances present in the cell.

Solvent Properties of Water. One important property of water is its high efficiency as a *solvent.* No other single liquid is capable of dissolving so many different substances. Water is the most effective solvent for inorganic compounds generally; and also many important organic compounds are soluble in water.

When a substance (the *solute*) *dissolves* in another substance (the *solvent*), the solute tends to become *dispersed* throughout the solvent. The ideal state of *true solution* is reached when all the molecules of the solute have become individually separated from the dissolving mass, and have scattered freely throughout the solvent. Thus when a crystal of sugar is dropped into a glass of water, the disappearance of the crystal indicates that the sugar molecules, which previously formed a compact and tangible mass, have become individually separated and distributed throughout the water.

The solvent capacity of water is important because the many compounds in protoplasm are dissolved in a common medium; and this intimate mixing of the different molecules greatly enhances their chemical reactivity. Dissolved substances interact together much more rapidly than mixtures in a dry state. Accordingly, much of the complex metabolism of the cell would not be possible if the protoplasmic dispersion medium could not encompass such a rich variety of chemical components.

Thermal Properties of Water. The freezing (0° C.) ar boiling (100° C.) points—between which water remains liquid state—represent the approximate extremes which are tc erable to protoplasm; and if temperatures in this range h not prevailed on the earth for many years, life as we know could not have been evolved. Likewise, the exceptionally hi *heat capacity* [3] of water plays an important role in the life organisms generally. When the temperature of the environme changes rapidly, that of the living body—due to its large co tent of water—changes much more slowly. Accordingly, orga isms have time to take measures of self-preservation wh drastic changes occur in the temperature of the environme A frog, for example, may sit on a rock in the broiling sun, wh the temperature of the rock—which has a relatively low he capacity—rises with considerable rapidity. But the temperatu of the frog rises much more slowly, and this gives ample tir for the frog to seek a nearby pond.

Another important *thermal property* of water is its exce tionally high *heat of vaporization* [4]—which provides a cooli factor in organisms generally. In the case of man and oth higher animals, perspiration is vaporized from the surface the body, and this process dissipates large amounts of he which otherwise would elevate the body temperature. In high plants, the process of transpiration likewise keeps the temper ture of the leaves below the lethal point; and at the same tin transpiration generates a force which draws more water up fro the soil (Chap. 12).

Chemical Activity of Water. Water participates in ma metabolic reactions in all cells. Hydrogen and oxygen are co stituents of virtually all organic compounds, and consequent

[3] The heat capacity of a substance specifies the quantity of heat (number calories) required to raise the temperature of 1 gram of the substance 1 deg Centigrade. For water, the heat capacity is *one* (cal.), an exceptionally hi value. Or, to use a different unit, one large calory (1 Cal.), which is des nated by the capital C, is required to produce a 1° C. elevation in the tempe ture of a *liter* (= 1,000 gms.) of water.

[4] The heat of vaporization (expressed in Calories) specifies the quantity heat required to vaporize one liter of a liquid, and the value for water (0.4 Cal.) is unusually high.

water frequently appears among the initial or end-products, when such compounds are metabolized in the protoplasm.

Water in Relation to Dissociation. *In solution* many molecules tend to *dissociate*, forming electrically charged fragments, called *ions*. Not all substances can dissociate appreciably, but the tendency, if present, always reaches a maximum when a substance is dissolved in *water*.

The dissociation of table salt (NaCl) is given in the following equation:

$$\underset{\substack{\text{molecular}\\\text{sodium chloride,}\\\text{in aqueous}\\\text{solution}}}{NaCl} \underset{\text{association}}{\overset{\text{dissociation}}{\rightleftharpoons}} \underset{\substack{\text{sodium}\\\text{ion}}}{Na^+} + \underset{\substack{\text{chloride}\\\text{ion}}}{Cl^-}$$

which shows that each molecule of NaCl, when it dissociates, liberates one sodium ion (Na^+) and one chloride ion (Cl^-).

The origin of the electric charges, which are characteristic of all ions, can be seen by inspecting the atomic structure of the NaCl molecule (Fig. 48). The sodium atom in uniting with chlorine gives up one electron, becoming the sodium ion (Na^+); and the chlorine atom becomes the chloride ion (Cl^-), by accepting an electron. So long as these ions remain united as the NaCl molecule, the electric charges neutralize each other; but if the ions separate—as they do when the salt is dissolved in water—the ionic charges become effective.

Not all ions are as simple as Na^+ and Cl^-, as may be seen in the following cases:

1. $$\underset{\substack{\text{sodium}\\\text{nitrate,}\\\text{in aqueous}\\\text{solution}}}{NaNO_3} \underset{\text{association}}{\overset{\text{dissociation}}{\rightleftharpoons}} \underset{\substack{\text{sodium}\\\text{ion}}}{Na^+} + \underset{\substack{\text{nitrate}\\\text{ion}}}{NO_3^-}$$

and

2. $$\underset{\substack{\text{magnesium}\\\text{chloride}}}{MgCl_2} \rightleftharpoons \underset{\substack{\text{magnesium}\\\text{ion}}}{Mg^{++}} + \underset{\substack{\text{chloride}\\\text{ion}}}{2Cl^-}$$

Generally speaking, *an ion is an atom, or group of atoms, which bears one or more electric charges.* Moreover, *positively*

charged ions are called cations; and *negatively charged ions are called anions.*

Electrolytes and Non-electrolytes. Some substances, such as sugars, starches, and fats, display no appreciable tendency to ionize, and such compounds are called *non-electrolytes;* but

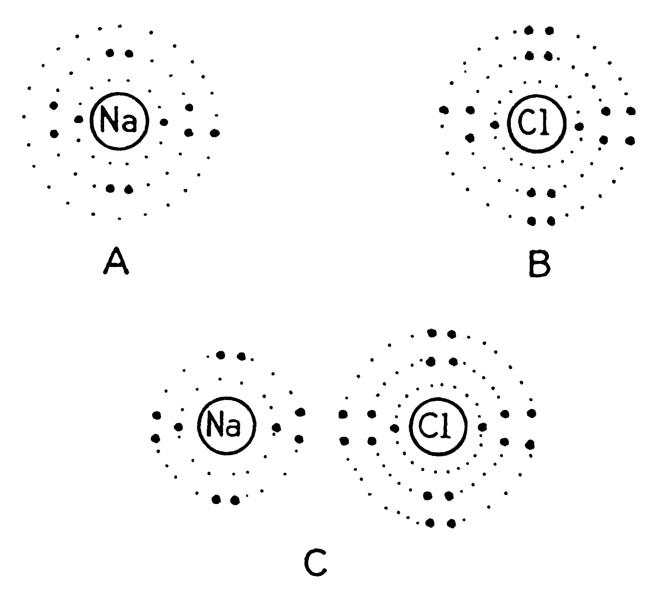


FIG. 48.—Chemical union between an atom of sodium (Na) and an atom of chlorine (Cl) to form a molecule of salt (NaCl). A and B, separate atoms of sodium and chlorine; C, a sodium chloride molecule. See text for further explanation.

other substances, such as salts and proteins, dissociate more or less strongly, and these are called *electrolytes.* Among the electrolytes, some are strong and others are weak, depending upon the proportion of the molecules of the given substance which undergo dissociation in aqueous solution.

Experimentally, electrolytes are distinguished from non-electrolytes by measuring the electrical conductivity of the substances dissolved in water. Water itself conducts electricity very poorly; and when pure water is placed between the poles in an electric circuit, scarcely any current flows. But if a strong electrolyte, such as sodium

chloride, is added to the water, the resulting solution is a good conductor. The current, in fact, is carried by the ions of the solution. The cations (in this case Na^+) migrate towards the *cathode* or *negative* pole; and the anions (in this case Cl^-) pass toward the *anode*, or *positive* pole. Accordingly, the conductivity of an aqueous solution is a good index as to the degree of dissociation of the solute molecules. In the case of non-electrolytes, such as sugar, the solution, as compared to pure water, displays little or no increase in conductivity.

Many compounds in the cell are strong electrolytes, which dissociate freely in the aqueous parts of the protoplasm. On this account, protoplasm itself will conduct electricity quite freely; and this fact is of considerable importance in every cell (Chap. 10).

Dissociation of Water: Hydrogen and Hydroxyl Ions. The conductivity of pure water is very small, but even this small conductivity is significant. It indicates that water dissociates in small degree, as is shown in the following equation:

$$\underset{\text{molecular water}}{H \cdot OH\ (H_2O)} \rightleftarrows \underset{\text{hydrogen ion}}{H^+} + \underset{\text{hydroxyl ion}}{OH^-}$$

Despite the fact that the ratio of dissociated to undissociated molecules in pure water is very small (1 : 555,000,000), the dissociation of water cannot be overlooked. Hydrogen ions (H^+) and hydroxyl ions (OH^-) are both *extremely* active ions, which participate, directly or indirectly, in all the metabolic reactions of every cell.

Acid, Basic and Neutral Solutions. All solutions are classified as *acid*, *basic* or *neutral—depending upon the proportion of hydrogen* (H^+) *and hydroxyl* (OH^-) *ions* which they contain. In acid solutions, the hydrogen ion (H^+) is more abundant than the hydroxyl (OH^-); in basic (alkaline) solutions, the hydroxyl ion is more abundant than the hydrogen; and in neutral solutions, the hydrogen and hydroxyl ions are present in equal numbers.

Pure water (HOH) displays a *neutral reaction*, because each dissociated water molecule liberates H^+ and OH^- ions in *equal* ratio (1 : 1). The reaction of protoplasm, however, is not precisely

neutral, since protoplasm may vary *slightly* in either an acid or a basic direction. Protoplasm contains many acid substances (p. 92) which liberate hydrogen ions, and many bases (p. 92) which yield hydroxyl ions; and interactions constantly occur between these compounds. Accordingly, local changes in acidity and alkalinity occur—although these shifts are very small. When *indicator dyes*—which change color according to the hydrogen ion concentration—are microinjected into a cell, it is found that the reaction of the *cytoplasm* is stabilized at a point very *slightly on the acid side of neutrality;* while the *nucleoplasm* is very slightly alkaline. Moreover, the cell *maintains* this *approximate neutrality* of the protoplasm; and if acids or bases accumulate unduly in any cell, the protoplasmic structure deteriorates, and death results.

Salts, Acids, Bases, and Their Respective Ions. Many different inorganic *salts* are found in protoplasm—and the same is true of inorganic *acids* and *bases*—except that these compounds are present in much *smaller amounts*. Moreover, all the inorganic salts, acids, and bases are highly dissociated into ions; and in protoplasm, the many ions continuously unite and disunite in various ways—as may be seen in Table III.

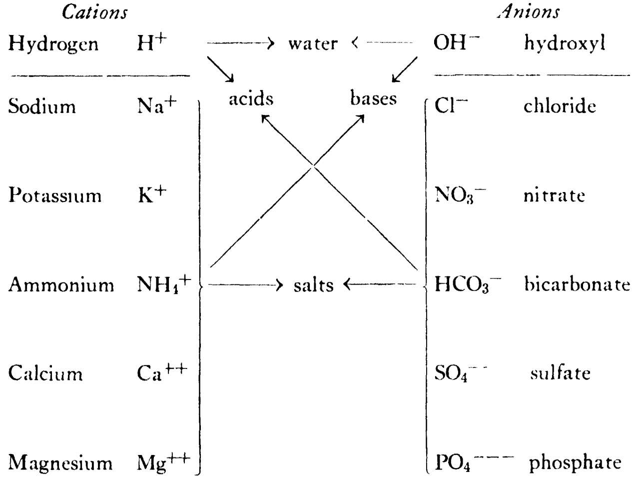
Table III also shows that the *classification of inorganic compounds* depends upon the presence or absence of hydrogen (H^+) and hydroxyl (OH^-) ions in the various compounds. An *acid substance* represents the union of hydrogen ion with any anion, *except* the hydroxyl; a *base* represents the union of hydroxyl ion with any cation *except* the hydrogen; and a *salt* is any cation, except H^+, combined with any anion, except OH^-. In inorganic chemistry, therefore, *water*, which represents a union between the hydrogen and hydroxyl ions, occupies a class by itself.

The hydrogen and hydroxyl ions in protoplasm are relatively less abundant than other ions—due to the fact that most of these ions remain *associated* as HOH (water). Consequently the manifold molecules, which momentarily are formed when oppositely charged ions come into contact, give rise mainly to *salts*—such as sodium chloride (NaCl), sodium nitrate ($NaNO_3$), etc. (see Table III). However, some hydrogen and hydroxyl ions are always present, so that protoplasm always contains traces of the various *inorganic acids* —such as hydrochloric acid (HCl); nitric acid (HNO_3), etc.; and

traces of *inorganic bases,* such as sodium hydroxide (NaOH), potassium hydroxide (KOH), etc. (Table III).

TABLE III

MAIN INORGANIC IONS IN PROTOPLASM



Origin of the four main kinds of inorganic compounds: water, salts, acids, and bases. Water is formed by a union between (H^+) and (OH^-) ions; acids are formed by H^+ ion uniting with any anion except OH^-; bases by OH^- ion uniting with any cation except H^+; and finally, salts are formed by any cation except H^+, uniting with any anion except OH^-.

Gases in the Protoplasm. All cells are permeable to the atmospheric gases, and these gases are soluble both in water and in protoplasm. Consequently, the gases of the air tend to enter all cells and to dissolve in the protoplasm.

Nitrogen (N_2), due to its abundance in the air (79 per cent), is always present in the cell; but free nitrogen is very inert chemically, and free N_2 does not participate in the metabolism of most cells—although the compounds of nitrogen are very important in metabolism. Considerable oxygen (O_2) also enters the cell, due to its abundance (20.96 per cent) in air; and oxygen takes part in many metabolic reactions. Without oxygen, in fact, most cells cannot maintain their structure and activities, except for relatively short periods. Very little (0.03 per cent) carbon dioxide (CO_2) is present in the atmosphere; but CO_2

is produced in the oxidative metabolism of all cells. In the cell much of the carbon dioxide unites chemically with water, forming a weakly acidic compound carbonic acid (H_2CO_3).

$$CO_2 + H_2O \rightleftarrows \underset{\text{carbonic acid}}{H_2CO_3} \rightleftarrows H^+ + \underset{\text{bicarbonate ion}}{HCO_3^-}$$

Organic Components of Protoplasm. Except when synthesized artificially, organic compounds occur only in living bodies, or in their products and remains. Organic molecules tend to be relatively large and complex; and usually organic molecules lack any strong tendency to ionize. However, the most important distinction between organic and inorganic compounds lies in the intrinsic composition. The element *carbon* (C), which rarely appears in inorganic chemistry, is present *in all organic compounds.* In other words, *organic chemistry is the chemistry of carbon compounds.* In fact, the commonest test to determine whether an unknown substance is organic or inorganic is the charring test. Virtually every organic compound decomposes and yields carbon, if it is heated drastically in a dry condition.

The unique capacity of carbon to form a great variety of compounds—which are segregated as a separate branch of chemistry—derives from the structure and behavior of the carbon atom. Carbon differs from most other atoms in that it is intermediate between the electro-positive atoms—which lose electrons, and the electro-negative atoms—which *gain* electrons —when they unite to form their respective compounds. Carbon can combine with either type of atom, and this capacity enriches the variety of carbon compounds. Also the valence of carbon is relatively high. By gaining, losing, or sharing the *four* valence electrons, carbon can unite with *four* other univalent atoms or atomic groups.

An even more important property of carbon is its capacity to unite with other carbon atoms. This property enables carbon to form a wide variety of chainlike and ringlike "molecular skele-

tons"; and in this way carbon is able to unite with many other atoms, forming very large complex molecules.

Table IV shows a series of organic compounds composed entirely of carbon and hydrogen. Here it should be noted that the different molecules are constructed in similar fashion, in that: (1) every carbon atom possesses four combining points;

Table IV

A SERIES OF RELATIVELY SIMPLE ORGANIC COMPOUNDS

Name	*Formula*	*Structure*
Methane	CH_4	H │ H—C—H │ H
Ethane	C_2H_6	H H │ │ H—C—C—H │ │ H H
Propane	C_3H_8	H H H │ │ │ H—C—C—C—H │ │ │ H H H
Butane.	C_4H_{10}	H H H H │ │ │ │ H—C—C—C—C—H │ │ │ │ H H H H
Pentane.	C_5H_{12}	H H H H H │ │ │ │ │ H—C—C—C—C—C—H │ │ │ │ │ H H H H H
Octane.	C_8H_{18}	H H H H H H H H │ │ │ │ │ │ │ │ H—C—C—C—C—C—C—C—C—H │ │ │ │ │ │ │ │ H H H H H H H H
or Generally	C_nH_{2n+2}	H H H H │ │ │ │ H—C—C—C - - - C—H │ │ │ │ H H H H

(2) each molecule is formed by a series of carbon to carbon linkages; (3) the linkage between any two consecutive carbon atoms mutually pre-empts one valence from each carbon; and (4) each hydrogen atom occupies just one valence point of any given carbon atom.

Kinds of Organic Substances. Living cells contain a very great variety of organic compounds. These carbon compounds are continually changing by interaction with each other; but certain kinds tend to be most abundant in the protoplasm. These most abundant organic compounds are divided into three main *classes*—the *carbohydrates*, the *lipids* and the *proteins*—which are distinguishable on the basis of their physical and chemical characteristics, and on the basis of their functions in the cell.

Carbohydrates. The most familiar carbohydrate compounds are the *sugars*, *starches*, *glycogens* and *celluloses*. Chemically all carbohydrates have much in common, although different carbohydrates may have different functions in the cell.

The chemical structure of carbohydrates can be exemplified by two specific compounds: (1) *glucose* ($C_6H_{12}O_6$), a white crystalline sugar, present in practically every cell; and (2) *sucrose* ($C_{12}H_{22}O_{11}$), the familiar sugar of the dining table. The formulae of these compounds show that (a) the only constituents of a carbohydrate are carbon, hydrogen and oxygen; (b) the hydrogen and oxygen display a ratio of 2 : 1 (as in water); and (c) six (or a multiple of six) carbon atoms are present. The first two points are true for *all* carbohydrates, and the third is true for a majority. Accordingly, *typical carbohydrates are compounds solely of carbon, hydrogen and oxygen, in which usually carbon atoms are present to the extent of six (or a multiple of six) and the hydrogen and oxygen are in a two to one ratio.*

Glucose. Glucose is the most important carbohydrate. In every cell glucose can provide not only energy, but also matter, for the synthesis of many other essential compounds.

Pure glucose, like table sugar, is a white crystalline sweet-tasting solid, which is very soluble in water. But compared to sucrose, glucose is more active chemically; and glucose, due to

the smaller size of its molecules, can pass through cell membranes more easily than sucrose.

Glucose as a Protoplasmic Fuel. The energy expended by a cell when it moves and performs its other activities, all comes from the decomposition of organic compounds in the protoplasm. These organic compounds possess a rich fund of intramolecular energy; and in serving as fuel, large energy-rich molecules continually decompose into simple end-products, liberating the balance of energy for the useful work of the cell. Moreover, many of these decompositions are *oxidative* in nature.

Among the *fuels* used by cells generally, glucose is very important. Most cells are able to "burn" glucose, and many cells use glucose in preference to other fuels.

The oxidation of glucose proceeds in many steps (p. 160), but the *overall* oxidation can be specified as follows:

$$\begin{array}{ccccccccc} C_6H_{12}O_6 & + & 6O_2 & \underset{\text{synthesis}}{\overset{\text{decomposition}}{\rightleftarrows}} & 6CO_2 & + & 6H_2O & + & E\ (\text{Energy}) \\ \text{1 mol. glucose} & & \text{6 mols. oxygen} & & \text{6 mols. carbon dioxide} & & \text{6 mols. water} & & \text{4 Cals. per gram of glucose} \end{array}$$

In other words, by uniting with six molecules of oxygen, each glucose molecule produces six molecules of carbon dioxide and six molecules of water; and in this oxidation, energy is liberated for the use of the cell.

Chemical Reactions in Relation to Matter and Energy. The oxidation of glucose exemplifies the nature of chemical reactions generally. In all chemical reactions one or more substances are transformed into one or more *other* substances by a *regrouping* of the same existing atoms. Accordingly, all chemical reactions display a *conservation of matter*—as is plain from two considerations. (1) The total weight of the reacting substances exactly equals the total weight of the resulting substances; and (2) the total number of each kind of atom remains unchanged when the reaction is completed. In the present case, for example, the glucose and oxygen which are consumed, weigh exactly as much as the carbon dioxide and water which are pro-

duced. Also the *equation* is *balanced*—since both the initial and the final products are constituted by 6, 12, and 18 atoms respectively, of carbon, hydrogen and oxygen.

Virtually all chemical reactions involve some kind of *energy* transaction. On this basis, in fact, chemical reactions are generally subdivided into two groups: (1) *exothermic* reactions, which discharge energy *to* the environment; and (2) *endothermic* reactions, which absorb energy *from* the environment.

Larger and more complex molecules generally possess a greater fund of intramolecular energy than a corresponding weight of smaller and simpler molecules. Consequently most *decomposition* reactions—in which larger molecules are fragmented into smaller ones—give forth energy *to the environment*. But conversely, most synthetic reactions—in which larger molecules are built from smaller units—cannot proceed without absorbing energy *from the environment*.

The foregoing equation shows that the oxidation of glucose is a typical decomposition. It is exothermic to the extent of 4 Calories per gram of glucose consumed. However, the same reaction proceeding in the opposite direction—and this occurs when a green plant cell absorbs sunlight and converts carbon dioxide and water into glucose and oxygen—is a typical synthesis, namely, *photosynthesis*. Photosynthesis is an endothermic reaction, and can occur only when sufficient energy in the form of light is available for absorption from the environment.

Glucose is employed more universally than other protoplasmic fuels. The cells of man's body, for example, derive much of their energy by oxidizing glucose. Man's blood stream carries a very constant supply of glucose, and the "blood sugar level" must be maintained at a minimum of about 0.1 per cent, if serious collapse is to be avoided (p. 428).

Synthesis of Other Carbohydrates from Glucose. Cells also use glucose as a raw material from which to synthesize other carbohydrates. In this case a number of glucose molecules unite chemically, forming larger types of molecules. Accordingly many carbohydrates are essentially aggregates, formed

by the chemical union of a greater or lesser number of glucose molecules.

Dehydration Synthesis. The commonest method by which cells synthesize larger molecules from smaller units, is by the process of *dehydration synthesis*. This type of reaction is shown by the synthesis of malt sugar (maltose), which occurs in many plant cells. Each molecule of maltose is formed from two molecules of glucose; and in the course of the reaction, one molecule of water is formed as a by-product.

$$\underset{\text{2 mols. glucose}}{C_6H_{12}O_6 + C_6H_{12}O_6} \underset{\text{hydrolysis}}{\overset{\text{dehydration synthesis}}{\rightleftarrows}} \underset{\substack{\text{1 mol.}\\ \text{maltose}}}{C_{12}H_{22}O_{11}} + \underset{\substack{\text{1 mol.}\\ \text{water}}}{H_2O}$$

The synthesis of maltose may be taken as the prototype for dehydration synthesis generally. In a dehydration synthesis, water is always formed as a by-product, because one molecule of water is eliminated at each point where union occurs between two smaller molecules. In the cell most large molecules, including carbohydrates, proteins, and fats, are built up by dehydration synthesis from various simpler molecules.

Hydrolysis. Hydrolysis is the opposite of dehydration synthesis, as is shown in the foregoing equation. Hydrolysis occurs when a larger molecule combines with water and fragments into smaller molecules.

Hydrolysis and dehydration synthesis occur very frequently in metabolism. Constructive metabolism involves the building of many complex substances from simpler chemical units, and frequently this involves a series of dehydration syntheses. Conversely, destructive metabolism often involves the hydrolytic splitting of larger molecules into simpler components. Hydrolysis reactions generally are exothermic, whereas dehydration syntheses are endothermic; but *usually* the quantity of energy involved is rather small.

Other Carbohydrates. *Monosaccharides.* The formula, $C_6H_{12}O_6$, is not specific for glucose. In fact this formula designates a group of simple sugars, among which *glucose*, *fructose*,

and *galactose* are the most important. These sugars differ from one another very slightly as regards the degree of sweetness, solubility, chemical reactivity and so forth. In the molecules of each, the same numbers and kinds of atoms are represented, but the *arrangement* of the atoms is not quite the same.

Disaccharides. From glucose and other monosaccharides the cell synthesizes complex carbohydrates as these are needed. Two monosaccharide molecules, chemically united, constitute a disaccharide, for which the general formula is $C_{12}H_{22}O_{11}$. The

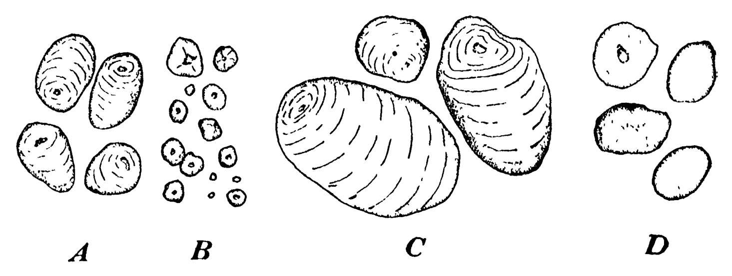


Fig. 49.—Starch grains from different plants, all drawn to same scale; A, arrowroot; B, corn; C, potato; D, wheat.

three most important disaccharides are *maltose* (malt sugar), *sucrose* (table sugar), and *lactose* (milk sugar). Each maltose molecule represents a union between two molecules of glucose; sucrose is formed from one glucose and one fructose; and lactose is constituted of glucose and galactose. Accordingly, all the disaccharides are formed by dehydration synthesis from the monosaccharides; and conversely, each disaccharide liberates the corresponding monosaccharides, when hydrolysis occurs.

Polysaccharides. These important substances include the *starches*, *glycogens*, and *celluloses*. All these compounds are derived from *glucose* by multiple dehydration synthesis. The starches and glycogens possess huge molecules, each representing a complex of almost a thousand glucose molecules, united chemically into a single unit; and the cellulose molecule is even larger. The exact number and arrangement of the glucose units differs somewhat in the different starches, glycogens and celluloses found in different cells.

All polysaccharides are relatively insoluble and tasteless. The starches (in plant cells) and glycogens (in animal cells) tend to be deposited in the form of definite *grains*, which can be seen in the cytoplasm (Fig. 49). Cellulose is deposited on the surfaces of plant cells, as a thin but visible sheet—the *cell wall.*

Cellulose has great importance as the chief component of cell walls and of *woody* materials generally. Starch and glycogen are also important—as reserve protoplasmic fuels. The cell can hydrolyze glycogen or starch, obtaining glucose for use at any moment. Meanwhile, the deposit of fuel remains safely in reserve. Due to the size and insolubility of polysaccharide molecules, neither starch nor glycogen can escape from the cell; and the chemical inertness of these polysaccharides safeguards them from deterioration (Table V).

TABLE V

CHEMICAL NATURE OF SOME FAMILIAR CARBOHYDRATES

Class	*General Formula*	*Specific Names*
Monosaccharides	$C_6H_{12}O_6$	Glucose, fructose, galactose
Disaccharides . . .	$C_{12}H_{22}O_{11}$	Maltose, (glucose-glucose) sucrose, (glucose-fructose) lactose (glucose-galactose)
Polysaccharides	$(C_6H_{10}O_5)_x$	Starches, glycogens, celluloses

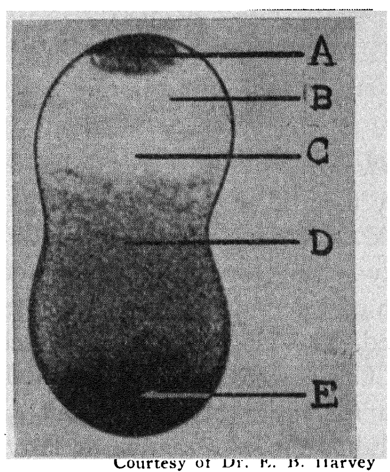
Lipids (or Lipins). All *fats* and *fat-like* substances are included among the lipids. *Physically*, the lipids are "greasy" substances, relatively insoluble in water, but readily soluble in such organic solvents as ether, chloroform, and hot alcohol. Lipids which are liquid at room temperature (about 20° C.) are commonly called *oils* (olive oil, cod-liver oil, etc.); but even *fats* such as butter, lard, tallow, etc., which are solid or semisolid at room temperature, are generally liquid at the body temperature of the warm-blooded animals in which they occur.

Because of their diverse *chemical* nature, lipids are not treated as a single group, but are subdivided into three groups: (1) the *true fats*, (2) the *phospholipids* and (3) the *steroids.*

The True Fats. The *true fats* include many familiar substances, such as olive oil, butter fat and beef fat. Beef fat

($C_{57}H_{110}O_6$) shows the typical chemical structure of a true fat in that: (a) true fats are composed entirely of C, H and O; and (b) the natural fats have large molecules, containing usually about 50 and 100 atoms respectively of C and H, but *only 6 atoms of O.*

The fats in protoplasm serve mainly as accessory fuels (Fig. 50). However, fats do not oxidize as readily as glucose, al-



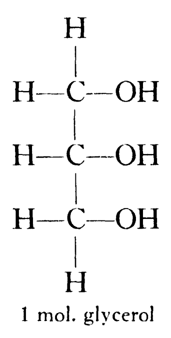
Courtesy of Dr. E. B. Harvey

FIG. 50.—The fatty materials of protoplasm are relatively light and rise to one end when a cell (such as this Arbacia egg) is centrifuged strongly. A, fatty materials; B, nucleus; C, clear protoplasm; D, lighter granules; E, heavier granules.

though the quantity of energy per gram of oxidized fat is considerably greater (9 Cals. as compared to 4). Much of the fat in complex animals such as man is localized in special cells, which collectively make up the *adipose tissue* of the body.

A molecule of fat represents a combination of simpler units which can be liberated by *hydrolysis.* In practice this hydrolysis is accomplished by boiling the fat in a strongly basic solution, although cells hydrolyze fats at ordinary temperatures. When hydrolyzed, each fat molecule liberates: (a) *one* molecule of *glycerol,* which is commonly called glycerin, and (b) *three* molecules which the chemist identifies as *fatty acid.*

Glycerol is a viscous, colorless, water-soluble liquid, possessing a formula of $C_3H_8O_3$, and the following chemical structure:



1 mol. glycerol

The *fatty acids* are less familiar than glycerol, although fatty acids are widely used, in the form of a water emulsion, as the "brushless" type of shaving cream. Dry crystalline fatty acids are white, waxy-feeling solids, which are not very soluble in water, although considerably more so than the fats from which they are derived. The most familiar fatty acid is *stearic acid*, $CH_3(CH_2)_{16}{\cdot}COOH$, which is obtained by hydrolyzing beef fat.

The formula for stearic acid, $CH_3(CH_2)_{16}{\cdot}COOH$, shows that one end (called the "head") of the fatty acid molecule is constituted by a special grouping of atoms (—COOH), which is the *carboxyl radical*. The carboxyl radical is written as —COOH, although its true structure is better shown by an expanded formula:

$$\begin{array}{l}—\text{C—OH} = —\text{COOH}\\ \quad\;\| \\ \quad\;\text{O}\end{array}$$

The carboxyl radical is important because all compounds possessing it are *acid* compounds. The hydrogen of the carboxyl is "loosely connected"; and this hydrogen dissociates as hydrogen ion (H^+) when an organic acid is dissolved in water. Thus *organic acids* may be specified by the general formula R—COOH, where the "R" stands for the "body" of the molecule, which varies in different compounds. Likewise the dissociation of an organic acid may be written:

$$\underset{\text{organic acid}}{R\cdot COOH} \rightleftharpoons \underset{\text{organic anion}}{R\cdot COO^-} + \underset{\text{hydrogen ion}}{H^+}$$

In the case of the fatty acids, the "body" (R) of the molecule represents a straight carbon chain in which all available combining points are occupied by hydrogen. Thus the specific formula of *palmitic acid* (from cocoanut oil) is $CH_3(CH_2)_{14}\cdot COOH$; and that of stearic acid (from beef fat) is $CH_3(CH_2)_{16}\cdot COOH$. Most natural fatty acids possess rather "long chain" molecules, although a few, such as acetic acid ($CH_4\cdot COOH$), are much simpler. Moreover, all naturally occurring fatty acids are constituted by an *even* number of carbon atoms (see above).

Plant and animal cells can synthesize fat by triple dehydration synthesis, providing glycerol and fatty acids are present in the protoplasm. This reaction may be shown as follows:

$$\underset{\text{1 mol. glycerol}}{\begin{array}{c} H \\ | \\ H-C-OH \\ | \\ H-C-OH \\ | \\ H-C-OH \\ | \\ H \end{array}} \quad \underset{\text{3 mols. stearic acid}}{\begin{array}{l} H-OOC\cdot C_{17}H_{35} \\ H-OOC\cdot C_{17}H_{35} \\ H-OOC\cdot C_{17}H_{35} \end{array}} \rightleftharpoons \underset{\text{1 mol. fat}}{\begin{array}{c} H \\ | \\ H-C-OOC\cdot C_{17}H_{35} \\ | \\ H-C-OOC\cdot C_{17}H_{35} \\ | \\ H-C-OOC\cdot C_{17}H_{35} \\ | \\ H \end{array}} + \underset{\text{3 mols. water}}{3H_2O}$$

When a cell uses fat as fuel, it first hydrolyzes the fat into glycerol and fatty acids, and then gradually oxidizes the products. Since C, H, and O are the only constituents of a fatty acid, the only end-products formed when a fatty acid is oxidized completely are CO_2 and H_2O. Disregarding the complex intermediary stages, the total oxidation of a fatty acid may be written:

$$\underset{\text{1 mol. fatty acid}}{C_{18}H_{36}O_2} + \underset{\text{26 mols. oxygen}}{26O_2} \rightarrow \underset{\text{18 mols. carbon dioxide}}{18CO_2} + \underset{\text{18 mols. water}}{18H_2O} + \underset{\text{approx. 9 Cals. per gm.}}{\text{Energy}}$$

Phospholipids and Steroids. The chemical complexity of phospholipids and steroids precludes an adequate brief description. One very common phospholipid is *lecithin,* an unstable

fatlike compound obtainable from egg-yolk. Lecithin is probably a structural component in all cells. The molecular structure of lecithin resembles that of a fat, except that one of the three fatty acids is replaced by phosphoric acid in combination with choline (an organic base).

The most familiar steroid substance is *cholesterol* ($C_{27}H_{45}OH$), a normal component of bile; and several hormones, including the sex hormones (p. 517), likewise belong to the steroid group. Cholesterol and the other steroids are constituted entirely of C, H, and O; but the "carbon skeleton" of a steroid is a complex of several interlinked *rings*, rather than a straight chain. Steroids are probably represented in all protoplasm, but their precise function is not very thoroughly understood.

Proteins. Proteins are all-important *structural* components in every cell. The best available evidence indicates that the various *genes*, the different *enzymes* (p. 122 ff.), the *pellicle*, and several other important components in cells generally, are all mainly of protein composition.

Chemically proteins are the most complicated of all substances. The molecules—even in such relatively simple proteins as gelatin and egg-albumen—are huge molecules, consisting of thousands of atoms. *The constituent atoms of natural proteins always include carbon, hydrogen, oxygen, nitrogen and sulfur;* almost always *phosphorus* is also included; and not infrequently the several other atoms commonly found in protoplasm are represented.

Protein chemistry was greatly simplified when it was discovered that each large protein molecule represents a chain of simpler units—the *amino acids*. The amino acids are liberated as separate molecules when a protein is subjected to hydrolysis. In fact when protein is hydrolyzed twenty-five different amino acids are yielded in varying proportions—depending upon the specific nature of the initial protein.

Amino Acids. Most of the amino acids may be represented by one general formula, $R—CH(NH_2)\cdot COOH$, which, in expanded form, may be written:

$$\begin{array}{c} R \\ | \\ H—C—NH_2 \\ | \\ C—OH \\ \| \\ O \end{array}$$

The "R" part of this formula represents the "body" of the amino acid molecule, which differs in each different amino acid; but the "head" of the molecule is the same in virtually every amino acid. In this "head" it is possible to identify two important radicals: (1) the *carboxyl* (—COOH), which determines the acidic properties of the amino acid, and (2) the *amino radical* ($—NH_2$), which accounts for the basic behavior of the amino acid (see below).

The three simplest of the *twenty-five different amino acids* are shown below. In *glycine,* R represents simply —H; in *alanine,* R = $—CH_3$; and in *cyteine,* R = $—CH_2·SH$; as may be seen in the following formulae:

$$\begin{array}{ccc} & & SH \\ & & | \\ H & CH_3 & CH_2 \\ | & | & | \\ H—C—NH_2 & H—C—NH_2 & H—C—NH_2 \\ | & | & | \\ COOH & COOH & COOH \end{array}$$

glycine alanine cysteine

The acidic behavior of the carboxyl radical is the same in an amino acid as in other organic acids (p. 102); but the basic behavior of the amino ($—NH_2$) group requires further explanation. Amino compounds act as bases, not by liberating hydroxyl ions in a solution, but by *removing* hydrogen (H^+) ions from the solution, as may be seen in the following equation:

$$R·NH_2 + H^+ + Cl^- \rightleftarrows R·NH_3^+ + Cl^-$$

The degree to which an amino acid acts as a base or acid depends upon the acidity or alkalinity of the solution in which it

is dissolved. In acid solutions, the amino radicals tend to neutralize the acidity by accepting hydrogen ions. But in basic solutions, the carboxyl radical tends to neutralize the excess of hydroxyl ions, by liberating hydrogen ions. This dual action is called an *amphoteric* behavior; and the amino acids and proteins are spoken of as *amphoteric* compounds. Moreover, proteins and amino acids are said to exert a *buffer action,* since they tend to *stabilize the reaction of a solution,* preventing it from shifting very much in either an acid or a basic direction, when acids or bases are added to the solution.

All the amino acids derived by the hydrolysis of natural proteins are crystalline solids which dissolve very freely in water. Amino acid molecules are all relatively small, and all can penetrate the membranes of the cell—which is distinctly not the case for protein molecules. Thus if protein substances are to be transported by the blood stream from one tissue to another in the body, they first are hydrolyzed into the derivative amino acids.

To maintain life, all cells must continue to synthesize their own peculiar and necessary proteins; and for this purpose every cell must obtain a full variety of the amino acids. Protein synthesis represents a multiple type of dehydration synthesis as indicated in the following manner:

```
H    R          H    R'          H    R''
 \   |           \   |            \   |
  N—C—H  peptid link  N—C—H  peptid link  N—C—H, etc.
 /   |          /    |           /    |
H    C.......[H]     C         [H]    COOH
    // \        |   // \        |
   O   [OH]—————↓  O   [OH]—————↓
              H2O              H2O
```

The variety of protein compounds that can be synthesized from the amino acids is practically limitless. Just as nearly an infinite variety of words may be formed from the 26 letters of the alphabet, so a practically limitless number of specifically

different proteins can be synthesized from the 25 known amino acids. Each variation as to the *number* and *position* of the different amino acids yields a variation in the properties of the resulting protein. In some cases the protein molecules resemble long free-ended chains with numerous side branches; in others, the ends of the chains, or of the side branches, are united, forming complex space-enclosing networks. Many proteins are soluble in aqueous media, although this property varies according to the acidity or alkalinity of the medium, and according to the amount and variety of salts present in the solution. Other proteins are very insoluble—as is true for the *scleroproteins*, which compose the hair, nails, and similar parts of the body. *Simple proteins* yield only amino acids upon hydrolysis; but the *conjugated proteins* also yield other substances—such as glucose (glycoproteins), or lipids (lipoproteins).

The wide variation of protein structure corresponds with the wide variation of living cells. Most cells have a protein content of about 15 per cent; and the proteins possessed by different cells are to a large extent specifically different. Proteins are the most characteristic and, excepting water, the most abundant compounds in all protoplasm. Their great complexity of chemical structure enables proteins to interact with a great number of other substances, forming the underlying basis of the complex system of chemical reactions which represents the total metabolism of every cell.

Summary of the Protoplasmic Composition. All living cells are composed of water, inorganic salts, proteins, carbohydrates, and lipids—together with smaller amounts of other substances. The average amounts of these compounds are shown in Table VI, although certain cells may vary considerably from the average.

In addition to the proteins, carbohydrates and lipids, protoplasm always contains smaller amounts of other, usually simpler, organic compounds. These include various *wastes,* such as urea (p. 430), intermediary *metabolites,* such as lactic acid (p. 562), *hormones,* such as adrenalin (p. 528), and *vitamins,* such as

TABLE VI

AVERAGE COMPOSITION OF PROTOPLASM

Kinds of Substances	*Per Cent by Weight*
Water	80
Inorganic salts	1
Proteins	15
Lipids	3
Carbohydrates *plus other substances*	1
	100

thiamin (p. 442). Many of these substances are of great functional significance, as will be apparent in the later chapters.

In the living cell the various compounds may be united into larger complexes: proteins with salts, carbohydrates, and lipins; steroids with other lipids; carbohydrates with inorganic salts, etc. Water associates with virtually all compounds dissolved in it; and in the case of such super-molecular aggregates it is not possible to distinguish clearly between chemical and physical combinations. Such linkages tend to be disrupted by the very methods usually employed to extract the protoplasmic substances from the cell; and much still remains to be learned about the chemistry of protoplasm. However, our present knowledge makes it plain that the complexity of the composition of protoplasm is sufficiently great to account for the great variety of living cells.

PHYSICAL STRUCTURE OF PROTOPLASM

Protoplasm is not just a mixture of chemical components—otherwise one should be able to create a living cell by merely adding the proper ingredients to a test tube. This, however, would be like expecting an accurately timed watch to emerge from a randomly piled assortment of cogwheels, screws, springs, etc. Obviously the creation of any functioning mechanism depends not only upon the materials of which it is composed, but also upon how these materials are formed and fitted into a functional relationship.

In the last analysis protoplasm, like other matter, is *particulate,* i.e., composed of particles. In protoplasm, however, the particles display a tremendous variability of size and shape (Fig. 50): from single molecules and ions, large and small, to various molecular aggregates—visible and subvisible. The size and shape of these particles greatly influence their behavior; and consequently it is necessary to study the dimensions very carefully.

Coarse, Colloidal and Crystalloidal Dimensions. Anything which is visible, either with the naked eye, or with a compound microscope, is designated as *coarse;* and above this borderline of visibility, vast space exists to accommodate the familiar objects of our universe. But even below this borderline, there is ample room for great variability in the size of submicroscopic particles.

Submicroscopic dimensions are subdivided into two categories, such that all larger particles—like protein and polysaccharide molecules—fall into the *colloidal size range;* and all smaller molecules—like water, salts, and monosaccharides—lie in the *crystalloidal range.* No real line divides colloidal from crystalloidal particles, and the various particles of protoplasm are finely and continuously intergraded in size. Arbitrarily, however, a line is set at 0.001 micron. Accordingly, particles having diameters between 0.1 micron (the limit of resolution of an ordinary compound microscope) and 0.001 micron are said to be colloidal; whereas particles having diameters less than 0.001 micron are crystalloidal.

On a practical basis, the appearance of a fluid indicates whether it is a colloidal or crystalloidal system. If the dispersed particles of a fluid are very small, i.e., of crystalloid dimensions, the fluid as a whole is clear and *transparent*—like a sugar or salt solution. The dispersed molecules or ions of such a solution are not large enough to block the light, which passes through. But if a fluid contains particles which are large enough to fall in the colloid range, the system has a cloudy or *translucent* appearance—like a starch or albumen solution. In this case the dispersed particles (large organic molecules) are not large

enough to block the passage of light waves completely, but they are large enough to scatter, or diffract, the light. Finally, a *coarse* system—like milk—appears *opaque*. In this case, the dispersed globules of butter fat are aggregated masses of molecules, and such particles are large enough to reflect light. Consequently, when milk is examined with a microscope, the *coarse* dispersed particles are individually visible.

Although colloidal particles are not large enough to be *seen* with a standard microscope, they are detectable by means of an *ultramicroscope*. This instrument resembles an ordinary microscope, except that it requires a more intense beam of light; and this beam is passed *horizontally*, rather than vertically, through the material under examination. Under the ultramicroscope, the colloidal particles of the protoplasm appear as a myriad of *bright specks* zigzagging in random directions against a black and empty background. Each particle is not large enough to reflect a definite pattern of light; but the particles are sufficiently large to scatter some of the light vertically toward the ocular. Thus the ultramicroscope shows very little as regards the precise color, shape, or size, of colloidal particles. It merely permits these particles to be identified and enumerated; and it reveals the nature of their movements. However, the *electron microscope*—which resembles an ordinary microscope except that a beam of electrons is used in place of light—is now used to photograph particles in the upper part of the colloidal range.

Another practical method of distinguishing between colloid and crystalloid particles is to test their capacity to penetrate a membrane such as cellophane or parchment. The pores or channels through a cellophane membrane appear to be just small enough to prevent the passage of colloid particles; but these pores are large enough to permit crystalloidal particles to pass through. Thus if a closed cellophane bag, filled with an aqueous solution containing glucose and starch, is immersed in water—after a short time glucose, but not starch, will begin to escape from the bag into the surrounding water. Such permeability considerations are very important in determining the exchange of substances between cells and their surrounding media. Gen-

erally speaking, colloidal particles are not able to penetrate the plasma membrane; and crystalloidal particles *may* or *may not* penetrate, depending upon a variety of factors (Chap. 6).

Size and the Motility of Particles; Brownian Movement. The absorption of heat by any kind of matter accelerates and intensifies the random movements of the component molecules, ions, and other particles. In fluid bodies like protoplasm, these *thermal movements* tend to scatter the particles evenly throughout the system. But the speed at which each particle moves, impelled by thermal energy at a given temperature, is governed largely by its size. When the diameter is doubled, the rate of movement is halved. In other words, the rate of thermal movement of a particle is inversely proportional to the square of its diameter. Accordingly the random movement of colloidal particles such as protein molecules, is very small compared to the movement of crystalloid particles, such as inorganic molecules and ions. The actual motion of colloidal particles as seen in the ultramicroscope, and the movement of small microscopically visible particles such as bacteria and starch grains, is not directly due to the thermal energy of these relatively large particles. Instead, it represents a phenomenon called *Brownian movement.* Brownian movement is exhibited by all small microscopic bodies as well as by ultramicroscopic particles generally. It arises from the bombardment of the larger particles by the surrounding multitude of smaller particles. In the protoplasm, the smaller particles responsible for this bombardment are chiefly water molecules. The bombardment is unequal from moment to moment, being heavier first on one side and then on another. Accordingly, the displacement of particles by Brownian movement is very irregular and unpredictable.

Solutions; Molecular Polarity. In an *ideal solution,* all the molecules or ions of the *solute* become individually separated and evenly dispersed throughout the dispersion medium—which is called the *solvent.* In actual solutions, however, the situation is complicated by the fact that the solute molecules or ions become associated with the molecules of the solvent; and the effective size of the dispersed particles in a solution tends to be

greater than expectations based on the molecular and ionic volumes of the dissolved substances. Accordingly, in protoplasm and other *aqueous* solutions, the solute particles are associated with a greater or lesser number of *water* molecules; or in other words, each solute particle is said to be *hydrated.*

The forces which attract water to the molecules or ions of the solute are mainly electrical. In many molecules, the electrical charges (protons and electrons) do not have a symmetrical placement in the molecule as a whole. In the case of water, for example, the whole molecule is an uncharged body, but the negative charges are more concentrated toward one end, and the positive charges toward the other. This endows water molecules with an electrical *polarity;* and in fact, water is designated as a *moderately polar* compound. Water is attracted to other molecules and ions in a solution with greater or lesser force, depending upon whether these other particles are *strongly* or *weakly polar* in their electrical configuration. Generally speaking, water, salts, proteins and simple carbohydrates are distinctly polar, whereas fats and polysaccharides are relatively *non-polar* compounds.

Among the components of protoplasm, those which dissolve in water include: most inorganic substances; sugars, amino acids, and other simple organic compounds; many proteins; and to a slight extent, the phospholipids and polysaccharides. Other lipids are virtually insoluble in water, although they dissolve mutually in each other. The water-soluble components in the protoplasm are all hydrated to a greater or lesser degree; and the salts, amino acids, proteins and phospholipids are also more or less strongly ionized. These considerations have great importance in determining the activities of the cell.

Suspensions and Emulsions. In a suspension or emulsion, the scattered particles consist of aggregates of the molecules of the dispersed substance. In a *suspension* the dispersed particles are considered to be *solid;* in an *emulsion* they are *liquid;* but in practice this distinction tends to be quite arbitrary. When the dispersed particles are very small, as in *colloidal* suspensions

and emulsions, it is difficult to determine whether the individual particles are in a solid or a liquid state.

The size of the dispersed particles in different emulsions and suspensions ranges from colloidal to microscopic or even macroscopic dimensions. In fact, colloidal suspensions and emulsions are sometimes so finely subdivided that they scarcely can be distinguished from colloidal solutions. Moreover, substances emulsified or suspended in water may even be hydrated and ionized, just as in true solutions.

Diphasic and Multiphasic Dispersions. In a true solution it is customary to regard the intermingled molecules and ions of the solute and solvent as all belonging to the same *phase* of the system. But in a suspension or emulsion it is necessary to distinguish between the *discontinuous* and the *continuous phases.* The discontinuous phase consists of all the larger dispersed particles or droplets, taken collectively; whereas the continuous phase is constituted by the dispersion medium itself, considered as a homogeneous mass. Milk, for example, is an emulsion in which the discontinuous phase is comprised by the microscopically visible globules of butter fat; and these globules float in the continuous phase, which is an aqueous solution containing milk sugar, various inorganic salts, and proteins.

A complex system such as protoplasm displays more than one discontinuous phase, each represented by a different kind of dispersed particle or droplet. Also in protoplasm one may find more than one continuous phase (see gel structure).

Emulsifying Agents; Adsorption. If olive oil and water are shaken together in a test tube, an unstable emulsion is formed which begins to break down as soon as the shaking is stopped. The agitation scatters a multitude of oil droplets throughout the water; but when the shaking ceases, these droplets begin to coalesce into larger and larger drops; and finally all the oil comes together as a separate layer, which floats on top of the water. If, however, a trace of soluble protein, or a small amount of soap solution, is added before shaking, a *stable emulsion* is obtained, and such an emulsion keeps its structure more or less indefinitely.

The foregoing example indicates that protein (or soap) can act as an *emulsifying agent.* In the stable emulsion most of the added protein accumulates at the surfaces of contact between the two phases, i.e., at the interfaces between the oil droplets and the water. Such an accumulation coats each droplet with a protective film which prevents it from coalescing with other droplets. The tendency for certain dissolved substances to be-

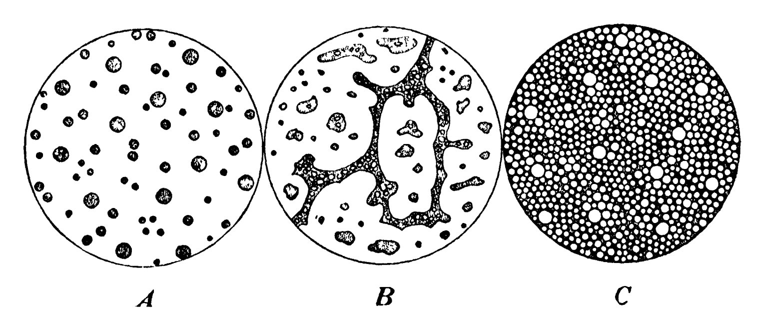


FIG. 51.—Emulsion of olive oil and water, as seen with the microscope; the oil contains a dye to make it darker. The changes in form of the emulsion are brought about by the addition of small amounts of a substance which changes the chemical constitution of the emulsifying agent. A, oil-in-water emulsion; water the continuous phase, oil the dispersed phase. B, intermediate form, the emulsion "breaking"; this state is very unstable, the two phases being in continual rapid motion and rearrangement. C, water-in-oil emulsion; oil the continuous phase, water the dispersed phase.

come concentrated at the interfaces of an emulsion or suspension is called *adsorption.* Many colloidal substances, particularly proteins and phospholipids, tend to be adsorbed heavily at the various protoplasmic interfaces. This stabilizes the finely emulsified droplets and delicately suspended particles which are so characteristic of living matter.

Phase Reversal. An emulsion such as is formed by shaking oil with water may take either of two stable forms: that of an *oil-in-water* emulsion (Fig. 51, A), or that of a *water-in-oil* emulsion (Fig. 51, C). The intermediate form (Fig. 51, B) is unstable. It tends to pass into either of the two stable forms; or it tends to "break" the emulsion structure, with a complete separation of the phases. These differences in the form of an emulsion depend chiefly upon the chemical nature of the emulsi-

fying agent. Any chemical change affecting the constitution of the emulsifying agent may therefore affect the stability of the emulsion and the relation of its phases. Without doubt, some of the changes in the appearance and consistency of the protoplasm are due to such *phase reversals,* which result from chemical changes wrought by the metabolism of the cell, or from chemical changes in the nearby environment.

Gelation and Solation. Protoplasm frequently alters its consistency, by undergoing gelation or solation. Like a gelatin solution, the fluid protoplasm of a cell may become set at a certain moment into a semi-solid elastic mass; and then later it may revert to a more fluid consistency. Recently the function of these changes has become clearer. The evidence indicates that the *contractility* of protoplasm depends upon its capacity to undergo gelation; and that many cell movements, such as *amoeboid movement,* cannot occur if the sol-gel changes in the protoplasm are inhibited.

The capacity to gelate is found in many colloidal systems, especially when the dispersed particles are elongate, like protein or polysaccharide molecules. In the sol condition such elongate particles behave more or less as separate units (Fig. 52, A). But as gelation occurs, attractive forces come into play between the colloid particles, so that the dispersed particles of the system become interlinked, forming a colloidal network which extends throughout the gel (Fig. 52, B). The water and other crystalloidal components are enmeshed by the gel framework and consequently the whole mass develops rigidity, elasticity, and contractility—properties which ordinarily are found only in solid systems.

The precise manner in which the elongate particles of a sol become linked together to form the colloidal framework of a gel, is not very clearly understood. The strength and number of the interconnections, and consequently the firmness of the resulting gel, are sensitive to many factors. Some of these factors are chemical, such as changes in the concentration of hydrogen ions and other substances in the solution; and some are physical, such as changes in temperature. Apparently gelation

in protoplasm is under the control of metabolism, which continually alters local conditions in various parts of the cell. All protoplasmic gels which have been studied behave oppositely to gelatin, at least in so far as temperature is concerned. Instead of undergoing solation as the temperature is raised, protoplasm undergoes gelation. Such a behavior is also exhibited by gels composed of myosin, the main protein present in muscle tissue.

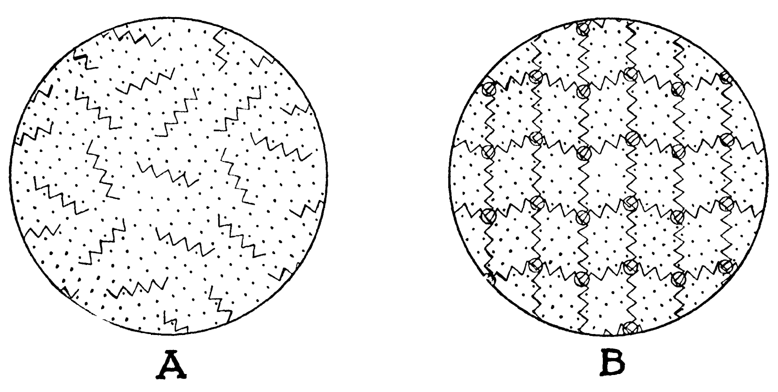


FIG. 52.—Ultramicroscopic structure of a sol and a gel (diagrammatic). A, a sol, in which the elongate colloidal molecules or particles are separate units. B, same system after gelation has occurred, in which the elongate particles are interlinked forming a colloidal network. Gels tend to be elastic and contractile.

In any event, once a gel framework had been assembled in the protoplasm, contractility can develop as a result of the folding of the interlinked molecules or other particles; and such folding processes are particularly characteristic of myosin and similar fibrous protein compounds.

Summary. Protoplasm represents a very complicated polyphasic dispersion, in which each phase displays a complex composition. Simultaneously, protoplasm is a crystalloidal, colloidal, and coarse dispersion, partly solution, partly emulsion and partly suspension. Sometimes protoplasm is in a gel state, and sometimes it is a sol.

The complex structure of living matter is not static; i.e., protoplasm ceaselessly changes, and these changes underlie the vital activities of the cell. The lipoid phases may alternately

undergo coalescence and separation in a fashion that may or may not involve phase reversal. The aqueous phases may remain homogeneous, as in the sol condition; or they may give rise to colloidal networks, as when gelation occurs. Such changes continually demand an expenditure of energy, which is supplied by metabolism. When energy-liberating chemical reactions cease, the finer protoplasmic structure breaks down, becoming less complex, more stable—or in other words dead.

But even as protoplasmic structure is dependent on metabolism, so metabolism is dependent on the living structure. The separate phases of the protoplasmic system constitute a series of microscopic and ultra-microscopic *reaction foci.* The separate films and surfaces at which a variety of the reacting components may be adsorbed and concentrated, limit, control, and regulate the metabolic reactions. Despite the size, each cell may be considered as a delicately organized "chemical engine." In the cell a wide variety of reactions go on simultaneously and more or less independently. When this delicate organization breaks down, the chemical activity does not cease immediately. Rather the metabolism becomes disorganized, unregulated and purely destructive, leading to a decomposition of many of the essential protoplasmic compounds.

Because protoplasmic structure and metabolism are mutually interdependent, a cell once dead cannot be "started up" again: the metabolism cannot be resumed in the absence of the living structure; and this structure cannot be restored without the metabolism. But the "death" of a cell is not usually a very abrupt and tangible change. In fact the intergradations between disease, injury and death are very subtle; but when the protoplasmic structure has degenerated beyond restoration, the cell is dead, however difficult it may be to determine exactly when this point of degradation is reached. From a scientific standpoint, the death of a multicellular individual, such as man, is still more indefinite. The many cells of the body do not all die at once. Some of the tissues may continue to live many hours after the man is "officially" dead. The usual verdict of death is given when the heartbeat and breathing stop, but these move-

ments can sometimes be restored many minutes later. But without respiration and circulation, no oxygen is carried to the body cells; and in the absence of oxidative metabolism, the protoplasmic structure gradually crumbles. Then sooner or later in each of the tissues the degradation becomes irreversible.

Thus all living organisms originate from the protoplasm of other living organisms; and the "endless" chain of specific structure and metabolism goes on unbroken, except when a species becomes extinct. Of the ultimate origin of the protoplasmic system, we have very little direct knowledge. Presumably protoplasm was evolved very gradually, through the millions of years of early geological time—from much simpler structures and processes.

TEST QUESTIONS

1. Among the elements represented in cells generally, which are:
   a. never present in uncombined form;
   b. present as the free element, as well as in combined form;
   c. present in the merest traces;
   d. exceptionally abundant;
   e. univalent;
   f. divalent;
   g. tetravalent?
2. In what way might you be able to convince your younger brother that water (and all others forms of matter) is composed of subvisibly small particles, or molecules?
3. Specify at least six kinds of energy; what are the primary distinctions between matter and energy?
4. Carefully define and exemplify each of the following terms: (a) molecules and atoms; (b) a substance and a mixture; (c) electrons and protons; (d) kinetic and potential energy.
5. Explain how the valence of an element is related to its atomic structure.
6. Distinguish between electropositive, electronegative, and inert atoms—giving an example in each case.
7. Discuss the physical properties of water in relation to the structural and functional characteristics of protoplasm.
8. Distinguish between electrolytes (strong and weak) and non-

electrolytes; what is the general importance of electrolytes in the cell?

9. Distinguish between the members of each group of terms:
   a. acid, basic and neutral solutions;
   b. an acid substance and an acid solution.
10. Explain a method by which the reaction (acidity or alkalinity) of the protoplasm of the nucleus and cytoplasm of certain cells has been measured; and state the results of such experiments.
11. What gases are usually present in protoplasm; how do these gases enter the cells; and why are they important?
12. Distinguish between organic and inorganic compounds on the basis of:
   a. occurrence in nature;
   b. chemical composition;
   c. molecular dimensions;
   d. capacity to dissociate.
13. Describe a simple test which can be used to differentiate between organic and inorganic substances. Explain.
14. Name four different carbohydrate substances and specify how each is important in various cells.
15. How are carbohydrates different from other organic substances?
16. To what extent is glucose used as a protoplasmic fuel? Explain, using the proper chemical equation.
17. Each chemical reaction represents a transformation of matter which proceeds in accordance with the law of the *conservation of matter*. Explain this statement using a specific reaction to exemplify the discussion.
18. What is the essential difference between an exothermic and an endothermic reaction? To what extent is it possible, by inspecting an equation, to decide whether a reaction is exothermic or endothermic?
19. Distinguish between:
   a. decompositions and syntheses;
   b. dehydration syntheses and other syntheses;
   c. hydrolysis and other decompositions.
20. Specify the end-products yielded by the complete hydrolysis of:
   a. starch (and cellulose);
   b. maltose;
   c. sucrose;

d. a true fat;
e. any simple protein;
f. any conjugated protein.

21. Provide at least one specific example, in each case:
    a. monosaccharide sugars;
    b. disaccharide sugars;
    c. fatty acids;
    d. amino acids.
22. As to chemical structure, how are amino acids (a) similar to, and (b) different from—fatty acids?
23. Explain the relation between:
    a. digestion and hydrolysis;
    b. true fats and phospholipids.
24. As to the constituent atoms, how do proteins differ from carbohydrates and fats?
25. All complete proteins liberate the same amino acids when fully hydrolyzed, and yet the proteins of different animals and plants are specifically distinctive. Explain.
26. Show by formulae how an amino acid can behave: (a) as an acid; and (b) as a basic substance.
27. Carefully explain: (a) the buffer action, and (b) the amphoteric behavior, of amino acids
28. Assuming that the chemical composition of protoplasm were fully known (which is far from true), what other difficulties would have to be surmounted to bring the "artificial synthesis of protoplasm" within the realm of possibility?
29. Explain how the course, colloidal and crystalloidal particles of protoplasm are to be distinguished on the basis of:
    a. actual dimensions;
    b. capacity to penetrate a cellophane membrane;
    c. capacity to penetrate the plasma membrane;
    d. microscopic visibility;
    e. detectability with the ultramicroscope;
    f. capacity to reflect or diffract light waves;
    g. thermal movements, including Brownian movement.
30. Briefly explain how the polarity of a molecule is related to its degree of hydration and its "effective size."
31. Mention three polar and two non-polar compounds present in protoplasm.

32. Distinguish between emulsions, suspensions, and solutions; give an example in each case.
33. Explain why phase reversal is possible in emulsions but not in suspensions.
34. Define the terms: (a) adsorption; (b) emulsifying agent; and (c) stable emulsion. Explain how these terms are interrelated.
35. Differentiate between a sol and a gel, using a gelatin "solution" to exemplify the discussion.
36. How does a gelatin gel differ from myosin and other "protoplasmic gels"?
37. Explain the relation between gelation and the contractility of protoplasm.
38. Describe the general structure of protoplasm using all the terms mentioned in Questions 29-37.

FURTHER READINGS

1. *An Introduction to Comparative Biochemistry*, by Ernest Baldwin; Cambridge, 1937.
2. *Interfacial Forces and Phenomena in Physiology*, by Sir William Bayliss; London, 1923.
3. *An Elementary Course in General Physiology*, by G. W. Scarth and F. E. Lloyd; New York, 1930.

CHAPTER 5

ENZYMES: SPEED AND ORDER IN CELL CHEMISTRY

IN PROTOPLASM many chemical reactions go forward with explosive speed. Yet if the reacting substances are removed from the cell and isolated in a test tube, they become very inert and no longer show much tendency to interact. Such a puzzling behavior led a few biologists to postulate a "vital force" which activates the protoplasmic molecules. But others continued to search for missing factors, and during the past twenty-five years the problem has been greatly clarified.

A relatively simple protoplasmic reaction will serve to illustrate this problem more specifically. Many plant and animal tissues constantly produce hydrogen peroxide (H_2O_2). This reagent does not accumulate in cells because it decomposes as fast as it is formed. In decomposing, peroxide liberates free oxygen, as is shown in the following equation:

$$\underset{\substack{\text{2 mols.}\\\text{hydrogen}\\\text{peroxide}}}{2H_2O_2} \rightleftarrows \underset{\substack{\text{1 mol.}\\\text{oxygen}}}{O_2} + \underset{\substack{\text{2 mols.}\\\text{water}}}{2H_2O}$$

In protoplasm this peroxide reaction goes forward very rapidly. Yet a pure aqueous solution of H_2O_2, such as is commonly employed as a disinfectant, is relatively stable. In a stoppered bottle peroxide keeps for months before it "goes flat," gradually freeing its content of O_2. Thus one phase of the problem is to ascertain why peroxide shows less reactivity in the test tube than in the protoplasm.

Catalysis. In many cases, the rate of a chemical reaction is greatly changed by the presence of a small amount of some specific reagent in the reaction medium. In the case of peroxide, for example, a very faint trace of manganese dioxide (MnO_2) will produce a thousandfold acceleration in the liberation of oxygen. If just a pinch of the black powder (MnO_2) is added to a test tube of peroxide solution, oxygen begins to come forth so rapidly that the mixture froths like beer. Moreover, it can be determined that none of the manganese compound disappears from the test tube, and consequently the same small sample of MnO_2 can foster the decomposition of peroxide in a quantity which is virtually without limit.

In the foregoing reaction, manganese dioxide may be recognized as a *catalyst*, and its action upon the peroxide is a typical example of *catalysis*. *A catalyst is any reagent that accelerates a chemical reaction without affecting the end-point, and without being destroyed when the end-point is reached.* A wide variety of catalysts are known in inorganic chemistry, and also there are many *organic catalysts.*

Enzymes, Especially Catalase. *Enzymes are organic catalysts produced by living cells.* Every cell contains a wide variety of enzymes, and without enzymes the cell loses its power to initiate and sustain its chemical activities.

Many enzymes can be extracted from the protoplasm without impairing their activity. For example, *catalase*, the peroxide-activating enzyme, can be obtained in dry crystalline form practically devoid of contaminating impurities. Such a purified enzyme displays tremendous activity. A small fraction of a gram of catalase, dropped into a test tube containing peroxide solution, gives rise to a most vigorous evolution of oxygen. In fact catalase accelerates the decomposition of peroxide much more effectively than manganese dioxide, when equivalent concentrations of the two catalysts are employed.

Small amounts of catalase are present in a wide variety of animal and plant tissues; and catalase activity can be demonstrated in many crude preparations. Thus when peroxide is poured upon an open wound, the frothing of the solution indi-

cates that catalase is present in the blood and serum which oozes from the wound. Also one may add the superficial scrapings from a raw potato to a peroxide solution and observe the bubbling, which results from catalase liberated by the damaged potato cells.

General Importance of Enzymes. Virtually all the many chemical reactions which sustain the life of the cell are activated by enzymes. Each different reaction generally depends upon a different enzyme, and all cells possess a wide variety of different enzymes. Most enzymes fulfill their duties inside the cell, in speeding the reactions of *metabolism;* but some enzymes are extruded from the protoplasm, to foster the reactions of *digestion.*

Specific Examples of Some Familiar Enzymes. The digestive enzymes of higher animals provide a number of familiar

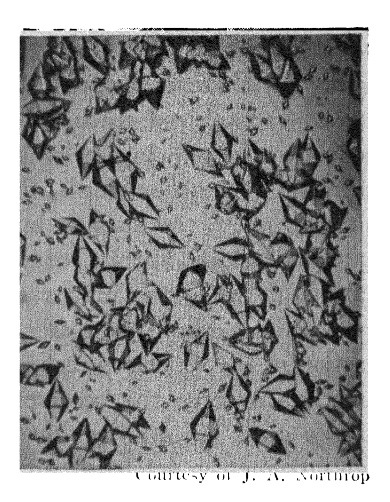
TABLE VII

SOME COMMON DIGESTIVE ENZYMES

Class and Species	*Source*	*Catalytic Action*	*Condition for Maximum Activity*
Carbohydrases			
Ptyalin, or salivary amylase	Saliva	Hydrolysis of starch (to maltose)	Neutral or faintly acid medium
Amylopsin, or pancreatic amylase	Pancreatic juice	Hydrolysis of starch (to maltose)	Alkaline medium
Maltase	Intestinal juice	Hydrolysis of maltose	Alkaline medium
Sucrase	Intestinal juice	Hydrolysis of sucrose	Alkaline medium
Lactase	Intestinal juice	Hydrolysis of lactose	Alkaline medium
Proteases			
Pepsin	Gastric juice	Hydrolysis of protein to proteoses	Strongly acid medium
Trypsin	Pancreatic juice	Hydrolysis of proteoses to polypeptids	Alkaline medium
Erepsin, or peptidase	Intestinal juice	Hydrolysis of polypeptids to amino acids	Alkaline medium
Lipases			
Gastric lipase	Gastric juice	Hydrolysis of fats	Acid medium
Steapsin, or pancreatic lipase	Pancreatic juice	Hydrolysis of fats	Alkaline medium

examples of enzyme activity. These enzymes can be extracted from the digestive juices of man and other mammals, and consequently they have been recognized for many years. All the enzymes listed in Table VII are obtainable from the digestive tract of man, and similar enzymes have been identified from species in every major group of the animal kingdom.

Chemical Nature of Enzymes. For many years enzymes could be identified only by their activity, and no pure enzyme had been isolated from any tissue. But in 1926 *urease* was obtained in pure crystalline form. This work started a tremendous advance in enzyme chemistry, and at the present time purified samples of more than thirty different enzymes have been isolated from a wide variety of plant and animal sources (Fig. 53).



Courtesy of J. H. Northrop

Fig. 53.—Crystals of purified pepsin.

Enzymes appear to be protein compounds. At least this is true for all that have been isolated; and those which have only been studied in crude form display many protein-like features. Like proteins generally, enzymes are unstable when heated, and most enzymes tend to lose their catalytic powers when the temperature approaches 40-50 degrees centigrade. The initial stages of *heat inactivation* are reversible with cooling, but if the temperature is maintained above a critical level, the catalytic power of the enzyme is lost permanently.

Some enzymes, like pepsin and trypsin, are *simple proteins*, being composed entirely of amino acids. But other enzymes represent proteins in combination with non-protein substances, which are called *prosthetic* substances. In some cases the prosthetic substance has been identified even though the enzyme as a whole has not been isolated. For example, it is known that

several vitamins, including thiamin (B_1) and riboflavin (B_2), are utilized as the prosthetic substances of several important oxidizing enzymes, in many animal and plant cells.

Alone, neither the protein nor the prosthetic substance possesses any catalytic activity. In some cases the linkage between the two cannot be ruptured without a complete and irreversible loss of enzymatic potency. However, sometimes when the two fractions of an enzyme are separated, full activity may be restored when the two are merely mixed together again.

Reversibility of Catalyzed Reactions. Theoretically the enzyme or inorganic catalyst does not determine the *direction* which a catalyzed reaction will take, i.e., the same enzyme is equally effective in accelerating a particular reaction in either direction. In other words, the direction of a reaction is determined not by the catalyst, but by other factors. Exothermic reactions, which liberate energy, tend to occur spontaneously, although when the proper catalyst is present, such a reaction proceeds at infinitely greater speed. To drive an exothermic reaction in the *reverse* direction—or to state the matter more directly—to force the occurrence of an endothermic reaction—*there must be some available source of energy.* Consequently an enzyme can accelerate an endothermic reaction only when a suitable source of energy is available.

Enzymes in Relation to Cell Structure; Coupled Reactions. Catabolic enzymes, which facilitate the exothermic reactions of the cell, tend to retain their activity after they are extracted from the protoplasm. But very few anabolic reactions can be duplicated outside the protoplasm. Apparently the enzymes which facilitate the endothermic reactions of the cell can only act in intimate association with highly organized structural components in the protoplasm. Each endothermic reaction depends upon a simultaneous exothermic reaction, and these reactions must be *coupled* in such a way that energy is transferred from the exothermic to the endothermic process. Such an energetic coupling of metabolic reactions depends in turn upon the integrity of the protoplasmic structure. The coupled reactions must occur synchronously and in close proximity to each other

and these conditions are usually realized only when the enzymes are suitably arranged in the colloidal structure of the protoplasm. In muscle, for example, a continued re-synthesis of adenosine triphosphate, an important organic component of the tissue, must go on if the muscle is to retain its contractile power; and this re-synthesis is coupled with the decomposition of phosphocreatine, another component of the fibers (see Chap. 23). Likewise the re-synthesis of phosphocreatine is coupled with the breakdown of glycogen in the muscle; and in turn, the restoration of glycogen is coupled with the oxidation of other substrates. In general, the exothermic processes of the muscle, such as glycolysis and oxidation, proceed readily after the protoplasmic structure has been disrupted by grinding the muscle; but the synthetic reactions are only achieved in the intact muscle. Despite the theoretical capacity of enzymes to act reversibly, the conditions necessary for reversal are not always available, and many enzymes exert their influence in one direction only. Moreover, even when a certain reaction is reversed in the protoplasm, the reversal does not necessarily involve the same enzyme as was utilized initially.

Other Characteristics of Enzymes. Enzymes tend to display a greater *specificity* than their inorganic counterparts. For example, a specifically different enzyme is necessary to hydrolyze each of the three common disaccharide sugars—sucrose, maltose and lactose (see Table VII). Frequently an enzyme acts only upon a single *substrate;* and even less specific enzymes act only on substrates with similar chemical structures.

The catalytic potency of many enzymes is exceedingly great. Ptyalin, the digestive enzyme present in human saliva, is capable of activating the hydrolytic breakdown of more than a million times its weight of starch. Theoretically no potency should be lost, even with infinite activity. But enzymes, like other proteins, do not possess a very stable structure. Consequently some deterioration occurs even though the catalyst is not consumed in the reaction which it catalyzes. Thus the maintenance of enzymic activity in the living cell depends upon a gradual replace-

ment of its enzymes, through the agency of constructive metabolism.

Mode of Action. Very little can be said about the precise mechanism of enzyme activity. Some experiments suggest that the structure of the enzyme molecule fits the configuration of the substrate molecule, more or less as a key fits its lock. Also there is evidence in many cases that the enzyme and substrate molecules unite together momentarily during the catalytic process. Such a union might free enough energy to launch the main reaction, which in turn might provide energy to liberate the enzyme from its temporary bondage to the substrate.

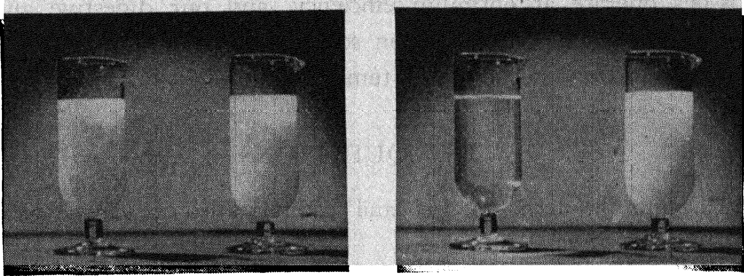
Sensitivity of Enzymes to Hydrogen and Other Ions. The activity of many enzymes is sensitive to the influence of various ions present in the reaction medium. This is particularly true as regards the hydrogen and hydroxyl ions. Each specific enzyme exhibits its most vigorous activity only when the acidity or alkalinity of the medium is adjusted to the proper level. Several examples of such sensitivity may be taken from the digestive enzymes of man. Pepsin, the powerful protease of the gastric juice, acts very sluggishly except when the medium is strongly acid; trypsin and the other enzymes of the pancreatic juice (Table VII) display full activity only when the medium is slightly alkaline. Ptyalin, the salivary amylase, requires a nearly neutral solution, and is quite inactive when sodium ion is absent from the medium. Most metabolic enzymes, which exert their influence in the protoplasm proper, attain greatest potency when the medium is approximately neutral.

Enzymes in Relation to Temperature. Heat accelerates the movements of molecules and ions, increasing the frequency of their contacts; consequently chemical reactions proceed more rapidly when the temperature of the medium is raised. As a general rule, in fact, each increase of 10° C. usually doubles, or even trebles, the rate of most reactions.

The foregoing temperature rule applies equally for both catalyzed and uncatalyzed reactions but enzyme systems present a very special case. Up to the point where the heat begins to destroy the enzyme, warming the medium increases the reaction

rate. But there is a critical temperature beyond which each enzyme cannot be carried. Above this point the enzyme becomes unstable and loses its catalytic power. Then the reaction rate drops quickly to the uncatalyzed level, which may be very slow, despite the elevated temperature.

The case of ptyalin will exemplify the thermal behavior of enzymes generally. If a small amount of saliva is mixed with



From sound film, *Digestion of Foods,* Encyclopaedia Britannica Films, Inc.

A B

FIG. 54.—Digestion of starch by saliva. A, two beakers were filled with an opaque suspension of starch in water. Some saliva (which contains ptyalin) was added to the left beaker only. B, later, the saliva has digested the starch, converting the large molecules into smaller molecules of double sugars, rendering the solution transparent in the left beaker, while the solution in the right beaker remains unchanged.

a starch solution, the starch is hydrolyzed to maltose (Fig. 54). This reaction proceeds rather slowly at 0° C., but more and more rapidly as the temperature of the test tube is raised. Maximum rapidity is reached at about 40° C. Then if the temperature is raised still further, chemical activity comes to a virtual standstill. Furthermore, if the damaging temperature is maintained for many minutes, no trace of amylase activity will persist after the system has been cooled again.

The thermal behavior of enzymes imposes serious limitations upon organisms generally. Most cells lose their capacity to carry on metabolism at temperatures above 40° C. A few organisms possess enzymes which are especially resistant to heat, and only such organisms are able to survive in exceptionally hot places. In most cells, the rate of metabolism, and hence the intensity of the life processes, changes as the temperature

varies from day to day, and from season to season. Thus the winter metabolism of most organisms subsides to a point where dormancy is inevitable. Only "warm-blooded" organisms, such as man and a few other vertebrates, have evolved a method of controlling their body temperature. In man, for example, the temperature seldom fluctuates more than a few degrees above or below 37.2° C. Accordingly the numerous enzymes of our tissues operate at optimum efficiency, and our digestive and metabolic reactions proceed on schedule, despite fairly drastic changes in the environmental temperature.

TEST QUESTIONS

1. Define the term catalyst and carefully describe any typical example of catalysis.
2. What is an enzyme? How and why are enzymes important in every cell and organism?
3. Name any four enzymes and specify the chemical reaction which is catalyzed by each.
4. Distinguish between enzymes and inorganic catalysts, on the basis of:
   a. chemical composition;
   b. stability at higher temperatures;
   c. specificity of action;
   d. sensitivity to hydrogen and other ions.
5. Is there any known relation between enzymes and vitamins? Explain.
6. *Explain why certain enzymes lose their power of catalysis when they are extracted from the protoplasm.*
7. Describe and *explain* the changes in the speed of reaction in the following cases:
   a. the decomposition of H_2O_2 in the presence of MnO_2 at 30°, 40° and 50° centigrade;
   b. the decomposition of H_2O_2 in the presence of catalase at 30°, 40°, and 50° centigrade.
8. How might the oxygen consumption of a man be affected by (a) fever and (b) a subnormal temperature? Explain.

FURTHER READINGS

1. *Chemistry and Methods of Enzymes*, by J. B. Sumner and F. G. Somers; New York, 1943.
2. *The Metabolism of Living Tissues*, by Eric Holmes; Cambridge, 1937.
3. *Crystalline Enzymes*, by J. H. Northrop; New York, 1939.
4. *An Outline of General Physiology*, by L. V. Heilbrunn; Philadelphia, 1944.

CHAPTER 6

OSMOSIS: MATERIAL EXCHANGES BETWEEN THE CELL AND THE ENVIRONMENT

METABOLISM in living cells is a never-ending process. It requires a ceaseless supply of raw materials and ceaselessly it produces a steady stream of end-products. These substances must pass in and out through the plasma membrane between the protoplasm and the surrounding medium.

The surrounding medium of the cell generally consists of some kind of aqueous solution. This solution may be the fresh or salt water in which the organism lives, or it may be a body fluid such as the blood and lymph of animals, or the tissue sap of plants. To enter the cell, the penetrating substance must display at least a minimum *solubility* in the fluid surrounding the cell and in the protoplasm of the cell itself. Ordinarily *only dissolved substances can pass through the plasma membrane.*

Not all dissolved substances can penetrate the plasma membrane with equal facility. The molecules of a substance may be too big, or they may encounter a variety of other interfering factors (p. 136). Accordingly the plasma membrane is designated as a *semipermeable membrane:* it is permeable to some substances, but not to all.

Osmosis is the exchange of components between two solutions which are separated by a semipermeable membrane. Accordingly each typical cell represents an osmotic unit. Dissolved substances are constantly exchanged across the semipermeable plasma membrane between the protoplasm on the one hand and the outside solution on the other, and the process of osmosis is of the utmost importance in every organism.

Diffusion. The spontaneous migration of molecules and ions within the limits of a single solution must be considered before dealing with the more complex process of osmosis. If any dissolved substance be concentrated more heavily in one part of a solution, this substance will spread gradually until its molecules (or ions) are evenly distributed throughout the whole solution. This process is called *diffusion.* It is caused by the random movements of all the particles (solute as well as solvent) which make up the entire solution. Essentially these random movements are a manifestation of the molecular kinetic energy (heat), which is characteristic of all matter except at absolute zero (−273.2° C.).

The direction which a chosen particle will take at any particular moment is entirely unpredictable. The particle may move in any direction, depending only upon its chance collisions with other particles or with the wall of the containing vessel. Nevertheless the *mass movements* of each *kind* of particle present in a solution *can be predicted accurately* on a statistical basis. These mass movements are governed by the fundamental *law of diffusion.* The particles of *each different substance present in a solution will diffuse from the region where that substance is more concentrated toward the region where it is less concentrated.* Moreover, diffusion will continue until every component reaches equal concentration throughout the whole solution. In the sugar solution of Fig. 55, for example, the mass movement of the water in a downward direction occurs simultaneously with the upward movement of the sugar molecules, until complete equality in the distribution of both kinds of particles is finally reached.

The *concentration* of *each* different substance present in a solution is of critical importance in determining the *direction* of the diffusion of *that substance.* The concentration of a substance specifies the *number of its particles present in a unit volume of the solution.* No two molecules or ions can occupy the same space at the same time, and therefore it follows that the concentration of any one substance cannot be increased without displacing an equivalent number of the particles of all other

components in the solution. Accordingly, whenever the total solute concentration is high, the concentration of solvent must be low; or whenever the concentration of one solute is increased, the concentration of the other solutes and of the solvent must undergo a corresponding decrease.

The foregoing relationships may be seen in the sugar solution which is diagrammed in Fig. 55. The sugar and the water molecules reach equilibrium by diffusing in opposite directions. But each is obeying the same fundamental law: each is escaping from the region of its greater concentration toward the region of its lesser concentration. In the top part of the original solution the higher concentration of water is determined by the lower concentration of sugar, and consequently the water diffuses downward. In the bottom of the test tube, the higher concentration of sugar corresponds to the lower concentration of water, and consequently the mass movement of the sugar molecules is in an upward direction.

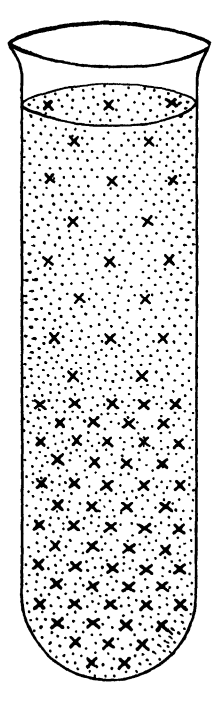


FIG. 55.—Diagram of free diffusion. A weak sugar solution layered on top of a stronger one. The attainment of equilibrium (equal distribution of all the molecules) depends upon *two* factors: (1) water molecules (*the dots*) diffuse downward from the upper solution where the water concentration is greater; and simultaneously, (2) sugar molecules (*the crosses*) diffuse upwards from the region where the sugar concentration is greater; i.e., each kind of molecule in a solution obeys the same law.

The velocity of diffusion is determined by a number of factors. The whole process depends upon thermal energy, and consequently equilibrium is attained more

quickly in warmer solutions. When the *concentration difference* is greater, the tendency of the particles to escape from the concentrated region is greater. Large particles diffuse more slowly than small ones (p. 111); and the more viscous the medium the slower the diffusion. Equilibrium is reached very slowly when the distances involved are macroscopic; but within microscopic and ultramicroscopic limits, the equalization of concentrations may be almost instantaneous.

Osmosis. If a semipermeable membrane be placed between two different solutions, an osmotic system is established. In such a system each kind of particle continues to obey the same law as determined its behavior in the single solution; i.e., *each substance tends to pass from the solution in which its concentration is greater to the one in which its concentration is lesser.* But in an osmotic system some of the component particles are unable to penetrate the intervening membrane. Therefore, an equal distribution of all the substances, if attainable, will depend upon the transfer of *only* those particles which are able to traverse the barrier.

In an osmotic system, substances which can penetrate the membrane continue to obey the law of simple diffusion. This is illustrated in Fig. 56, which shows the exchange of oxygen

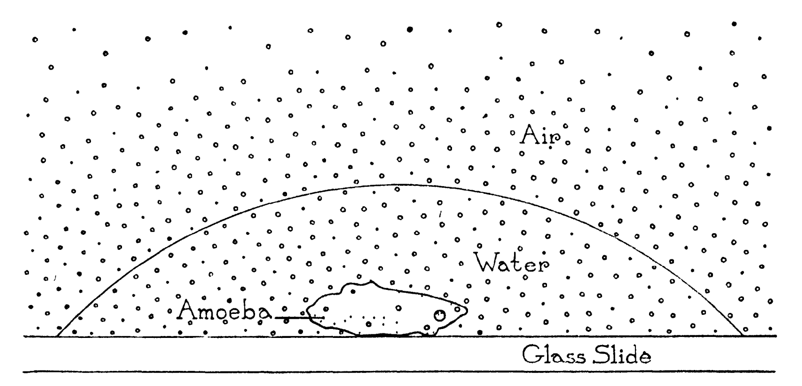


FIG. 56.—Diagram showing the exchange of oxygen (the circles) and carbon dioxide (the dots) between the protoplasm of an Amoeba and the surrounding water. Both substances obey the same law—passing toward the region of lowest concentration; i.e., into the protoplasm, in the case of oxygen; and into the environment, in the case of carbon dioxide.

and carbon dioxide which occurs in animal cells. Both oxygen and carbon dioxide are freely soluble in the protoplasm as well as in the surrounding water; and both can pass very freely through the plasma membrane. Thus a steady supply of O_2 molecules streams into the living cell so long as the concentration of oxygen remains relatively high in the outside medium. Inside the cell the concentration of O_2 is low because free oxygen is used for oxidative metabolism as soon as it enters the protoplasm. The O_2 concentration in the surrounding water tends to remain relatively high, since this water remains at equilibrium with the 20 per cent of oxygen in the supernatant air. Likewise carbon dioxide in leaving the cell, follows a similar gradient. In the protoplasm carbon dioxide is produced continuously by metabolism. Consequently CO_2 reaches a higher concentration relative to the outside water, which maintains equilibrium with the small amount (0.03 per cent) of carbon dioxide in the atmosphere.

Permeability of the Plasma Membrane. Such non-protoplasmic membranes as the pellicle and cell wall are freely permeable to most of the substances that normally impinge upon the cell, and it is the plasma membrane which exerts a main control over all osmotic processes. The permeability of the plasma membrane, which is very complex and variable, depends not only upon the nature of the impinging particles, but also upon the changing conditions inside and outside the cell. Permeability differs in different cells and sometimes on the different sides of the same cell. Nevertheless, certain generalizations can be made, and these are summarized in Table VIII.

The factors which determine the capacity of a given substance to penetrate the cell are not completely understood, although the size of the molecules is certainly important. In general, larger molecules experience more difficulty in traversing the membrane; and *colloidal molecules generally display a negligible penetrability*. But molecular size is not the only factor; otherwise the inorganic electrolytes (salts, etc.) would enter the cell more rapidly than such substances as glucose and amino acids. In the case of electrolytes, the interfering factor appears

Table VIII

CAPACITY OF VARIOUS SUBSTANCES TO PENETRATE THE PLASMA MEMBRANE

Very Rapid	*Rapid*	*Slow*	*Very Slow*	*Virtually No Penetration*
Gases Carbon dioxide Oxygen Nitrogen Fat solvents Alcohol Ether Chloroform	Water	Simple organic substances Glucose Amino acids Glycerol Fatty acids	Strong electrolytes Inorganic salts Acids Bases Disaccharides Sucrose Maltose Lactose	Complex (colloidal) compounds Proteins Polysaccharides Phospholipids, etc.

to be the electric charge carried by the ions of these substances. The living membrane itself maintains an electric charge (usually negative in sign, p. 207), and this charge tends to repel ions of the same charge. And since one type of ion in a solution cannot abandon the oppositely charged ions—without setting up a counter electric force—blocking one type of ion is almost equivalent to blocking both.

The great freedom afforded to the passage of fat solvents, such as alcohol and ether, represents another problem in cell permeability. Fat solvents pass through the membrane more rapidly than water, and this fact has led to a belief that fat solvents enter the cell by a special route: via lipoid phases in the membrane structure. Under normal circumstances, however, very small quantities, if any, of fat solvents are present in the protoplasmic system.

The Water Equilibrium of the Cell. The *bulk* of all solutes present in protoplasm are proteins, lipids, and inorganic salts, i.e., substances which penetrate the plasma membrane very slowly if at all (see Table VIII). Accordingly, the solvent, water, can enter or leave the cell very quickly compared to most of the solutes present; and water is more abundant in the system

than all other components combined. These facts are of great importance. They mean that the burden of establishing osmotic equilibrium between the cell and the surrounding solution falls mainly upon water. If a cell is placed in an unbalanced solution, in which the concentration of water is drastically different compared to the protoplasm, so great a quantity of water will enter or leave the cell that the living structure will be destroyed.

Isotonic Solutions. An *isotonic* solution, essentially, contains a concentration of water just equal to that in the protoplasm which it surrounds. This condition is realized only when the total concentration of solutes[1] (taken collectively) in the solution and the protoplasm is likewise equal. In an isotonic solution, the water exchange between the cell and the solution is exactly balanced. Owing to the random movement of molecules, water continues to escape across the membrane, but the escaping water is exactly balanced by an equivalent amount of water which enters the cell simultaneously. As a general rule the *blood and lymph* of animals are *isotonic to the cells.* In the blood stream, for example, the red blood cells are in osmotic balance with the surrounding plasma. Under these conditions no net gain or loss of water occurs and consequently the cells are preserved from abnormal changes of volume. But if red cells are studied in an artificial medium such as a salt solution, abnormal changes are bound to occur unless the artificial solution is made isotonic to the protoplasm (e.g., 0.9 per cent NaCl).

An isotonic solution contains a concentration of non-penetrating (or very slowly penetrating) solute which approximates the total concentration of non-penetrating solutes (proteins, phospholipids, salts) in the protoplasm. Otherwise an equality of the water concentrations inside and outside the cell is not possible. Various non-penetrating solutes may be used in the preparation of an isotonic solution, although the inorganic salts, especially NaCl, are most frequently employed. Best results are obtained from salt mixtures in which Na^+, K^+, Ca^{++} and Mg^{++} ions are represented in the proper proportions, since otherwise the normal semi-permeability of the plasma mem-

[1] Disregarding the small amounts of rapidly penetrating solutes (e.g., O_2)

brane gradually deteriorates. In the various kinds of "Ringer's Solution," the proper quantity and the proportions of inorganic salts vary considerably from one kind of animal to another. In transfusion fluids, which are used in emergencies to replace the blood plasma, a considerable proportion of protein is included with the salts. Various foreign proteins have been tried as substitutes for the normal plasma proteins, but not with much success. The main difficulty has not been to obtain the proper osmotic conditions, but to find foreign proteins which will remain in the blood stream and which are not toxic to the organism.

Hypotonic Solutions. A hypotonic solution contains a relatively low concentration of non-penetrating solute (compared to the protoplasm of the cell which it surrounds). Because of the low concentration of solute, the water concentration in a hypotonic solution is relatively high. Therefore, cells placed in hypotonic solution tend to imbibe water and to swell. The passage of water from the external solution where the concentration is higher, into the cell where the concentration is lower, conforms, of course, with the fundamental law of osmosis and diffusion. If the protoplasm can imbibe enough water to come into equilibrium with the surrounding solution, the swelling will stop. Otherwise, the swelling continues until the membranes around the cell are ruptured, and the cell as a whole is destroyed. When human red blood cells are put in a solution containing only 0.2 per cent NaCl (instead of the 0.9 per cent salt present in an isotonic solution), the corpuscles swell and burst so quickly that no opportunity is afforded for examining them with a microscope.

Plant and animal cells are very different in their capacity to tolerate submersion in hypotonic solutions. Pond water, since it contains only very small quantities of the inorganic salts and other non-penetrating solutes, is extremely hypotonic to all cells. Nevertheless pond water is the normal habitat of a great variety of unicellular forms. In the case of aquatic *plants,* such as Spirogyra, the great strength of the cellulose wall prevents the cells from swelling unduly. As water enters by osmosis from

the hypotonic medium, the protoplasm of the plant cell is forced outward against the unyielding cell wall. When a sufficiently high internal pressure is generated, the further entrance of water is prevented. This high internal pressure, which is called *turgor*, is characteristic of plant cells generally. The turgor pressure of a normal plant cell may rise to several atmospheres before a further influx of water is stopped. Typically the medium surrounding a plant cell remains hypotonic to the protoplasm, but turgor constitutes a counterforce which prevents more water from entering the cell.

If a plant is deprived of water, the individual cells lose turgor and the tissues become wilted. Such a wilted tissue (e.g., a limp lettuce leaf) may regain its normal crispness and turgidity if it is returned soon enough to fresh water. But should the cells be killed from loss of water, the wilted tissue never regains turgor. At death, the plasma membrane becomes indiscriminately permeable to virtually all solutes, and consequently the normal osmotic behavior of the cells is lost.

Unlike plant cells, most animal cells cannot tolerate exposure to drastically hypotonic solutions. The pellicle is not sufficiently strong to generate much turgor. Consequently most animal cells continue to swell and will burst if the influx of water is excessive. This phenomenon is called osmotic *cytolysis*. Animal cells can withstand moderately hypotonic solutions, however, since the incoming water may dilute the protoplasm sufficiently to establish equilibrium. When the water concentration on either side of the membrane becomes equal, no further swelling will occur.

Many Protozoa constitute a special case. These animal cells have become adapted to live in fresh water. To counteract the constant seepage of water into the protoplasm, these species have developed contractile vacuoles (Fig. 57). Such vacuoles prevent the cells from swelling by collecting water from the protoplasm and pumping it back into the environment. Just how the water is forced to move against its osmotic gradient in passing from the protoplasm into the vacuole is not clearly understood. But it is known that the cell must expend energy in performing

this *work*. This energy comes from metabolism; and if a Protozoan is treated with a metabolic poison, the contractile vacuole stops working. Then the cell begins to swell and eventually it will burst, unless the activity of the contractile vacuole is restored in time.

Hypertonic Solutions. A hypertonic solution, compared to the protoplasm of the cell which it surrounds, contains a relatively high concentration of non-penetrating solute. Since the

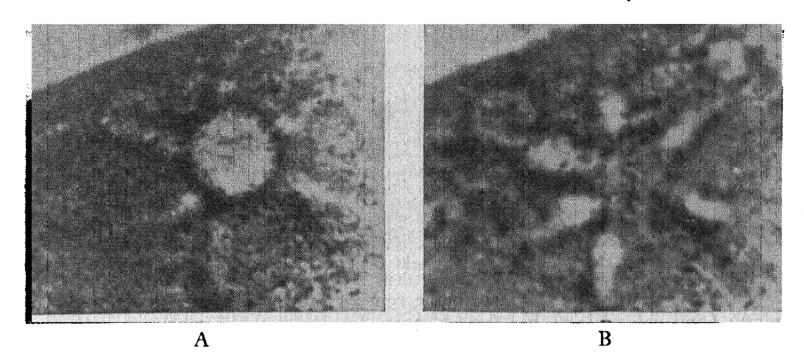


FIG. 57.—Greatly magnified view of a contractile vacuole in a Paramecium; A, filled to capacity; and B, just emptied. Note that the radiating canals, which conduct fluid into the vacuole, can be seen more clearly when the vacuole is empty.

solute concentration is high, the concentration of water in a hypertonic solution is relatively low. Therefore cells placed in hypertonic solution tend to lose water and shrink.

Plant and animal cells behave differently when they undergo shrinkage in hypertonic solution. The pellicle of many animal cells, being flexible, becomes wrinkled as the cell loses volume. This wrinkled, shrunken appearance, which can be seen in the red blood cells of Fig. 22, is described as *crenation.* The lesser volume of the crenated cells is due mainly to a loss of water. Water is by far the most prevalent of the substances capable of penetrating the membrane, and consequently equilibrium is established largely by the escape of water. The shrinking of the cell continues until finally the water concentration in the protoplasm is reduced to the level of the outside medium. In some cases, when the loss of water is not drastic enough to destroy the

living structures, the cell may regain its original volume, if it is returned to an isotonic medium. But if the cells are severely damaged by the loss of water, hypertonic shrinkage is irreversible.

The appearance of plant cells in hypertonic medium is quite different. The cell wall, being more rigid than the pellicle, maintains its original form, while the protoplasm continues to shrink. The resulting condition, which is shown in Figure 58,

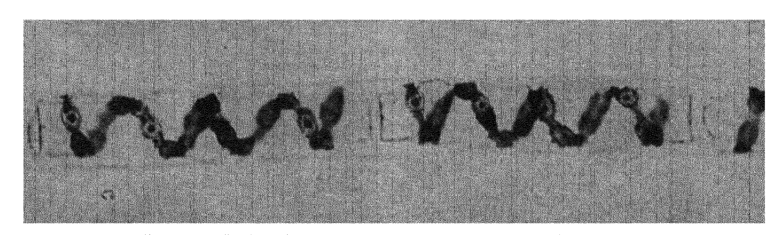


FIG. 58.—Plasmolysis as seen in the cells of Spirogyra. Note that the cytoplasm (and chloroplast) has shrunk away, leaving a gap between the plasma membrane and the cell wall.

is called *plasmolysis*. The protoplasm of the plasmolyzed cell occupies only a part of the space enclosed by the cellulose wall. Plasmolysis is likewise reversible, providing the plasma membrane is not damaged in the process.

Deplasmolysis. Instead of using a strong salt solution to plasmolyze a plant cell, one can use a hypertonic solution of glucose. Compared to the ions of a salt, glucose molecules can penetrate the cell more rapidly. Nevertheless the rate of penetration of the glucose is so slow compared to water that an initial plasmolysis occurs as soon as the cell is placed in the hypertonic solution. In a moderately hypertonic glucose solution, however, the plasmolysis does not endure indefinitely. Within about ten minutes the protoplasm shows signs of swelling, and within half an hour the protoplasm again occupies all the space within the encompassing cell wall.

The original plasmolysis is due to a very rapid equalization of the water concentration inside and outside of the plasma

membrane; and as soon as the concentration of water in the protoplasm is reduced sufficiently, the shrinking ceases. But later, the slow penetration of glucose begins to be significant. Glucose is the only solute present in the outside medium, and the concentration of glucose in the solution is greater than in the protoplasm. Consequently glucose slowly enters the cell, which disturbs the equilibrium which was reached when the protoplasm stopped shrinking. As glucose enters, the water concentration increases in the outer solution and decreases in the protoplasm. Consequently, the entrance of glucose is continuously accompanied by an entrance of water. Gradually, therefore, deplasmolysis occurs, and finally the plant cell regains its normal turgor.

Animal cells, crenated in hypertonic solutions of slowly penetrating solutes, likewise do not remain crenated. Gradually such cells also regain their original volume. In fact, an animal cell, lacking the protection of a strong external wall, may continue swelling, and may undergo cytolysis in a solution which originally was distinctly hypertonic.

Summary. Since the semipermeable plasma membrane intervenes between the protoplasm and surrounding solutions, each typical cell displays many of the attributes of an osmotic system. Any substance which can penetrate the membrane will pass out of the cell if it is more concentrated inside than outside; and will pass into the cell if the outside concentration is greater. The end-products of *destructive metabolism* such as carbon dioxide, water and other simple substances are all able to pass freely through the membrane. Due to their constant production the concentrations of these substances inside the cell tend to be higher than outside and consequently they continuously tend to leave the protoplasm. Substances which are used up in metabolism, such as oxygen or glucose, tend to enter the cell from the surrounding solution. The very fact that these substances are consumed or converted into other substances as metabolism proceeds tends to keep their concentrations in the protoplasm generally lower than in the outside medium. The products of *constructive metabolism*, on the other hand, are mainly colloidal

substances (proteins, polysaccharides, phospholipids, etc.) which cannot penetrate the membrane. Consequently these essential components of the protoplasm cannot escape despite their relatively high internal concentrations.

The water equilibrium between the cell and its environment assumes a very critical importance—first because water is by far the most abundant substance both inside and outside the cell, and second because water penetrates the cell membranes much more rapidly than most of the solutes present in the system. Plant cells are protected against a rapid and lethal influx of water from a surrounding hypotonic solution by the strength of the cell wall. This permits the development of a turgor pressure high enough to counteract the osmotic force under which the water continues to seek entrance into the cell. Animal cells, in contrast, cannot be maintained in a hypotonic medium unless some special mechanism like the contractile vacuole is present to deal with excess water as fast as it enters. In hypertonic solutions both plant and animal cells are equally vulnerable. No cell can lose too high a proportion of its water without suffering irreversible deterioration.

Not all exchanges between the cell and the environment can be ascribed to osmotic forces. Some cells (such as Amoebae and white blood cells) can take in relatively large visible masses of undissolved material by engulfing them. Also some cells can force water or dissolved substances to pass against a concentration gradient which normally would send these substances in the opposite direction. Such phenomena do not "contradict" the laws of osmosis any more than lifting a weight "contradicts" the law of gravity: they simply show that some other force is at work. In osmosis the various substances move *spontaneously*, impelled by the kinetic energy of the molecules or ions themselves. When a substance is moved "against the osmotic tide" some other forms of energy, derived from metabolism, are being expended by the cell. If the metabolism of a cell is temporarily depressed, as by asphyxiation or poisoning, all "anomalous osmotic phenomena" cease and the laws of simple diffusion and osmosis then hold sway.

TEST QUESTIONS

1. Define the term *osmosis*. What is the basis for describing the typical cell as a minute osmotic system?
2. What is diffusion; how is it energized?
3. State the general law which governs the *direction* of diffusion.
4. Explain why the solute and solvent (in the system shown in Fig. 55) continue to diffuse in *opposite* directions until equilibrium is reached.
5. Explain why the plasma membrane is typical of semipermeable membranes generally.
6. Arrange the following substances in an order which will designate their relative speeds in penetrating the plasma membrane: sucrose, oxygen, proteins, sodium chloride, glucose, starch, and ether.
7. Name three factors which have an important bearing on the capacity of a substance to pass through the plasma membrane.
8. Assuming that pure water is separated from a protein solution by a membrane which is permeable to water but not to protein, how would the system approach equilibrium?
9. Assuming that a cell is immersed in pure water, how would the system approach equilibrium?
10. In addition to the fact that water can traverse the plasma membrane more readily than the bulk of the solutes ordinarily present inside and outside the cell, what other factor places the burden of attaining equilibrium mainly upon water?
11. Explain the respiration of an Amoeba (Fig. 56) on the basis of diffusion and osmosis. What is the common law which determines the movement of both the O_2 and the CO_2?
12. What is an isotonic solution? Give one specific example. What determines the balanced exchange of water between the cell and such a solution?
13. A solution which is isotonic to one cell is not necessarily isotonic to another. Explain.
14. Carefully identify each of the following terms: (a) cytolysis, (b) plasmolysis, (c) crenation, (d) deplasmolysis, (e) turgor.
15. In each of the following cases, what observable change would occur when the cells are placed in the specified solutions:
    a. an Amoeba in a *very* weak (hypotonic) salt solution?
    b. a red blood cell in the same solution?

c. a plant cell in the same solution?
d. a plant cell in a strong (hypertonic) salt solution?
e. a plant cell in a hypertonic glucose solution?
f. a red cell in a hypertonic salt solution?
g. a red cell in a hypertonic glucose solution?
h. an Amoeba in a hypertonic glucose solution?

16. Carefully *explain* the effects described in parts a, b, c, d, e, and f of Question 15.

FURTHER READINGS

1. *Textbook of Experimental Cytology*, by James Gray; New York, 1931.
2. *An Outline of General Physiology*, by L. V. Heilbrunn; Philadelphia, 1943.
3. *Unresting Cells*, by Ralph W. Gerard; New York, 1940.

CHAPTER 7

ANIMAL CELLS AND THEIR NUTRITION

NUTRITION includes all processes which have to do with obtaining and utilizing *food*—and obviously these matters are very important in every living thing. In animals, food furnishes the only source of energy; and in all organisms, food is the only source of matter for sustaining and increasing the living structure. Without food no plant or animal can maintain life, except during periods of virtual dormancy.

A food is any substance which an organism obtains from its environment and utilizes in its metabolism. Some foods serve primarily as protoplasmic fuels; others as raw materials for the synthesis of essential protoplasmic compounds—but every food in one manner or another participates in the metabolism of the organism. Moreover, it is necessary to realize that the "foods" of our common experience are actually *mixtures* of many *food substances.* Steak, for example, consists of a high proportion of water, a variety of inorganic salts, considerable amounts of protein, fat, and carbohydrate, and a number of other individually distinct food substances. Only a few of the foods of man are highly purified single compounds, such as table salt and sugar. Moreover, what is a food in one organism is not necessarily a food in another (Table IX).

Modes of Nutrition; the Animal vs. the Plant. Typical animals and plants are distinguished by very fundamental differences in their nutrition. Green plants require only inorganic foods, but *animals must obtain at least a minimum of organic foods,* in addition to their inorganic requirements. Water, carbon dioxide and an assortment of the inorganic salts are all that

TABLE IX

PRINCIPAL FOOD SUBSTANCES—SOURCES AND USES IN ORGANISMS

Food Substances	*Principal Uses in the Organism*	*Usual Source*
Oxygen	Essential for oxidation of organic compounds in both plants and animals; oxidative metabolism important as a source of *energy*.	Present in the atmosphere and (in solution) in the waters of the earth; liberated by green plants.
Water	An essential structural component in all protoplasm and body fluids; participates in many metabolic reactions; used by green plants for the synthesis of glucose.	Abundant in the environment as soil water, lake water, etc.; present in virtually all natural foods.
Carbon dioxide	Used mainly by green plants as a source of carbon in the synthesis of glucose and other organic compounds.	Abundant in the environment as a component of the atmosphere and (dissolved) natural waters; plants diminish, animals replenish the carbon dioxide of the environment.
Salts	Essential components in all protoplasm and body fluids. Take part in many metabolic reactions.	Abundant in the environment as components of the soil, and as solutes in natural waters; present in almost all natural foods.
Proteins	Animals utilize protein foods in synthesizing the essential proteins of their own protoplasm; but plants use inorganic nitrogen compounds for this purpose. Animals also obtain energy from protein foods.	Protein parts and remnants of other organisms. Ultimate origin mainly from the plants.
Carbohydrates	Animals utilize carbohydrates in synthesizing essential protoplasmic compounds; plants synthesize these compounds from CO_2 and H_2O. Carbohydrates yield energy on oxidation, in both plant and animal cells.	Ultimate origin mainly from plants.
Fats (lipids)	Animals require fatty foods for synthesis of essential compounds; plants derive these compounds indirectly from CO_2 and H_2O. Fats yield energy (on oxidation) in animals and (to a limited extent) in plants.	Ultimate origin mainly from plants.
Vitamins	Essential structural components of the protoplasm.	Synthesized by plants (see Chap. 17).

the green plant needs as raw materials for the synthesis of the various organic components of its protoplasm; and the typical plant can live and grow indefinitely so long as these simple foods are available. But an animal cannot do this; an animal's food requirements are on a higher level of complexity. Compared to plant cells, animal cells have more limited powers of synthesis, and animal metabolism cannot be maintained in the absence of organic foods such as pre-formed proteins, carbohydrates, fats and vitamins (Table IX).

As a group, animals are quite similar as to their food requirements; and the same is true for green plants. Accordingly the nutrition of the typical animal is referred to as *holozoic* nutrition in contrast to the *holophytic* nutrition of green plants.

The *holozoic* mode of nutrition is associated with the develment among animals generally of many structures and activities which are not found among plants. The animal must obtain organic foods, and these compounds exist only in the bodies and remnants of other organisms. Therefore the animal is constantly faced with the necessity of finding and apprehending other organisms. This necessity has determined an evolution of highly developed sensory, nervous and muscular structures, which are so characteristic of animals, but not of plants. The essential foods of a plant are all inorganic substances which are widely distributed in the environment. The plant does not have to seek them out. Rooted to a single locality, a typical plant remains constantly in direct contact with all its necessary foods.

Other structures, generally present in animals, but absent in plants, are the organs of the digestive system. A digestive system is necessary in animals because most organic foods, such as proteins, are colloidal in their molecular dimensions. Such colloidal molecules cannot be absorbed into the cells of the animal until they have been digested into crystalloidal fragments. Therefore typical animals possess a digestive cavity wherein the colloidal components of the food are chemically altered in preparation for absorption.

Nutrition of Unicellular Animals; Holozoic Nutrition. One-celled animals, such as Amoeba, sustain themselves in a

fashion that is strikingly analogous to the nutrition of larger animals, including man. In obtaining and utilizing food, and in disposing of the waste products, all animals perform essentially the same processes and achieve essentially the same ends. Accordingly it is possible to describe the nutrition of Amoeba under the same eight headings (*ingestion, digestion, egestion, absorption, distribution, metabolism, respiration* and *excretion*) as are employed for holozoic organisms generally.

Ingestion. The Amoeba, as seen in a drop of pond water, slowly approaches its living or non-living food, engulfing the

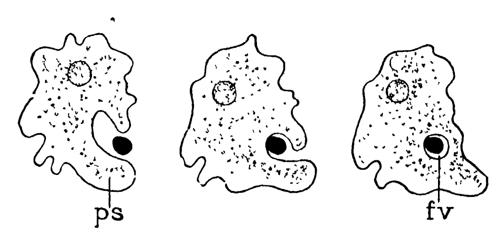


FIG. 59.—Amoeba ingesting a particle of food. ps, pseudopodium; fv, food vacuole.

entire mass. Gradually the *pseudopodia* extend around the food, forming a *food* cup (Fig. 59), and finally, when the lip of the cup closes, a *food vacuole* is formed. This primitive digestive cavity now contains a quantity of pond water, together with the organic food, which is to be digested (Fig. 60).

Ingestion is the process by which an animal takes food into its digestive cavity. Although the method of ingestion varies in different animals, the end-result is always the same. Paramecium (Fig. 61) swims about by means of its *cilia,* which also serve to sweep bacteria and other finely suspended particles of organic food through the *mouth* and *gullet,* into the *food* vacuole (Fig. 62). Or a frog catches a fly with a swift thrust of the tongue, and carries its prey into the mouth for swallowing. Or a man manipulates his food with implements and introduces it into the upper part of the digestive tract. But whatever the method, the result is quite the same. Food is taken into some special cavity where digestion will begin.

Courtesy of Encyclopaedia Britannica Films, Inc.

FIG. 60.—A living ciliate (dark oval body) being ingested by Amoeba. The pseudopodia are about to close around the prey.

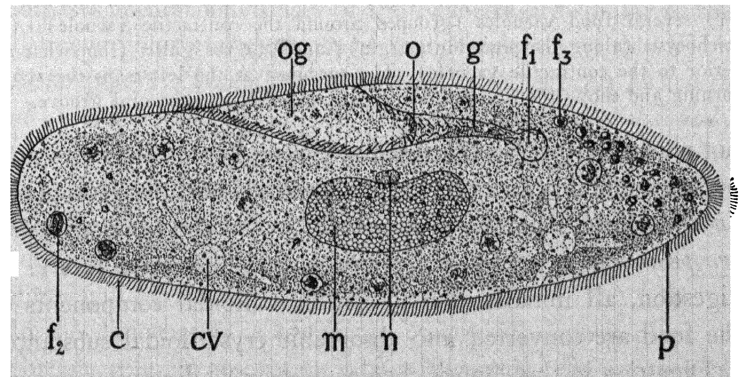


FIG. 61.—Paramecium. n, micronucleus, or true nucleus; m, macronucleus; p, pellicle; c, cilia; cv, contractile vacuole; og, oral groove; o, mouth; g, gullet; f1, food vacuole just formed; f2, food vacuole during the process of digestion; f3, food vacuole at or near the completion of digestion and absorption.

Digestion. The crystalloidal components of the Amoeba's food, such as water or salt, do not require digestion. Such foods are absorbed directly from the digestive cavity into the surrounding protoplasm without preliminary preparation. But the colloidal molecules of proteins, polysaccharides, fats, etc., can-



Courtesy of Bausch and Lomb Optical Co., Rochester

FIG. 62.—Living Paramecia, photographed at a magnification of about 250 diameters. In the posterior (broader) end of the right specimen one can see (1) several food vacuoles (grouped around the contractile vacuole); (2) trichocysts (along the posterior margin); and (3) the gullet (somewhat anterior to the contractile vacuole). The specimen at the left is in the act of turning and shows the oriented beating of the cilia, and the oral groove.

not penetrate the vacuolar membrane; and such molecules must be fragmented before they can be absorbed into the protoplasm. *In all animals digestion is a series of hydrolytic reactions which are promoted by enzymes secreted into the digestive cavity.* By digestion, all initially non-absorbable colloidal components of the food are converted into absorbable crystalloidal substances.

Digestion in the Amoeba begins as soon as digestive enzymes are secreted by the protoplasm into the food vacuole. Only traces of these enzymes are necessary. The digestive enzymes of Amoeba and other animals include several proteases. These proteases hydrolyze the proteins of the engulfed food, liberating

amino acids which dissolve in the vacuolar water. Likewise there are carbohydrases which act upon carbohydrates, digesting them mainly into glucose; and lipases which convert the fats into glycerol and fatty acids. All of these end-products of digestion are quite soluble in the aqueous content of the vacuole and all are capable of penetrating the vacuole membrane.

The digestive enzymes of lower animals such as the Amoeba and those of higher animals including man display many similarities. In the Amoeba, during the first ten minutes of digestion, the content of the food vacuole displays a distinctly acid reaction, indicating that some acid is secreted into the vacuole along with the enzymes. This acid phase of digestion in the Amoeba has its counterpart in digestion as it occurs in the human *stomach.* In the stomach our food is subjected to the action of an acid *gastric juice,* which contains a very active *protease,* pepsin. Probably pepsin, or a pepsin-like protease, is also present in one-celled animals, although the specific digestive enzymes of the Amoeba have not been isolated—due to the technical difficulties of handling such small organisms. During the later stages of digestion, the vacuolar content becomes distinctly alkaline. This indicates that the later-acting proteases, as well as the lipases and carbohydrases of the Amoeba, are similar to the well-known intestinal enzymes of higher animals (Table VII).

Absorption. *Absorption,* in animals, *is the process by which food substances pass from the digestive cavity into the body proper.* In fact, the digestive cavity can be regarded as a portion of the environment which is encompassed by the animal. While the food remains in the digestive cavity, it does not subserve any useful function. Accordingly digestion is merely a preliminary to absorption.

In the Amoeba, as in organisms generally, osmosis plays an important role in absorption. After digestion, the content of the food vacuole consists of an aqueous solution of simple sugars, amino acids, glycerol, fatty acids, etc. These substances can penetrate the vacuole membrane, and as a result of digestion, each of the end-products tends to reach a relatively high concentration in the vacuolar fluid. But these substances are con-

stantly consumed in metabolism, and therefore they remain at a relatively low level in the protoplasm surrounding the vacuole. Accordingly each food substance tends to pass spontaneously from the vacuole into the cell.

The water and inorganic salts included in the vacuole at the time of its formation are also absorbed into the protoplasm, the former very rapidly and the latter very slowly. Initially the pond water which is engulfed along with the organic food, is distinctly hypotonic. Accordingly a newly formed vacuole tends to shrink for several minutes, by losing water to the surrounding protoplasm. But later the vacuole enlarges, because the soluble end-products of digestion accumulate, making the vacuolar fluid hypertonic to the protoplasm. Finally, however, the vacuole undergoes a permanent shrinkage, owing to the slow absorption of organic solutes, together with a quantity of water sufficient to keep the vacuolar fluid isotonic with the protoplasm. Eventually just a small vestige of the vacuole remains, and such an "old" vacuole contains only a few residual granules of non-digestible material. These digestive wastes cannot be absorbed and must be ejected from the cell.

In higher animals food substances are absorbed into the blood and lymph, rather than directly into the protoplasm; and among animals generally, osmosis plays an important part in the absorption of substances from the digestive cavity, although other factors sometimes modify the situation. In the higher animals also, there is always a residuum of non-absorbable material which must be eliminated from the digestive cavity.

Egestion. *Egestion represents the elimination of non-absorbable materials from the digestive cavity.* In the Amoeba egestion is essentially the reverse of ingestion. The nearly empty food vacuole comes into contact with the plasma membrane at any point; and suddenly the vacuolar granules are spilled into the outside medium. In Paramecium, an old vacuole circulates in the cytoplasm until it reaches a fixed point, called the *anal spot.* At the anal spot, which is situated near the posterior end of Paramecium, the pellicle is relatively weak, or perhaps absent; and egestion can occur as it does in the Amoeba. Higher animals

generally possess a tubular digestive passage, and egestion, or *defecation*, occurs through the *anal opening*.

The composition of the *egestive wastes*, or *faeces*, varies according to the food habits of the particular animal. Herbivorous animals always have large remnants of cellulose from the woody parts of ingested plant tissues. This potential source of glucose (from the hydrolysis of cellulose) is partly lost, however, because *cellulase* is not included among the digestive enzymes of most animals. Carnivorous diets leave smaller residues of indigestible materials, such as bone and gristle; and in all animals small quantities of salts and water escape absorption.

Distribution. *Distribution represents the transportation of substances throughout the body of the organism.* In animals, absorbed foods must be carried from the digestive cavity to the other parts at a rate commensurate with the metabolic needs. Also, metabolic wastes must be transported to the site of elimination; and hormones and other substances must be carried from part to part in the body.

Distribution is not a very serious problem in one-celled animals, because diffusion and osmosis are adequate to disseminate the foods and other substances within such narrow limits. But larger animals have developed circulating fluids, such as blood and lymph, which accelerate the distribution.

In the Amoeba, absorbed foods can diffuse quite rapidly throughout the cytoplasm, and by osmosis the foods also pass into the nucleus. Moreover, the protoplasm constantly flows, as the Amoeba moves in search of food, and the protoplasmic streaming tends to accelerate distribution.

Metabolism. *Metabolism—the sum total of all chemical reactions occurring in the protoplasm of an organism*—represents the most essential phase of nutrition. All other nutritional processes are quite *accessory* to metabolism, since other nutritional processes merely provide the raw materials for metabolic activity, or remove the metabolic wastes after they have been formed.

Metabolism accomplishes two main objectives in every organism: (1) it liberates *energy*, which finds tangible expression in

the movements and other activities of the organism; and (2) it achieves the synthesis of new organic compounds, which are necessary for the growth and maintenance of protoplasmic structure. On this basis, in fact, the metabolism of each organism is subdivided into two major parts: (1) *Catabolism* includes all decomposition (exothermic) reactions—which provide energy for the organism; and (2) *Anabolism* embraces all synthetic (endothermic) reactions—which create new organic components in the protoplasm.

The metabolism of even the simplest cell involves a wide variety of chemical changes, catalyzed by a correspondingly wide variety of intracellular enzymes. And although quite a few metabolic reactions have been duplicated outside of the cell, many details of intermediary metabolism, especially in lower animals, still remain unknown.

Regardless of details, food substances in the protoplasm of an animal cell such as Amoeba, are launched upon a series of chemical changes. In an anabolic direction these reactions give rise to new proteins, lipids, carbohydrates, etc.; and these substances together with absorbed water and salts, become organized into new protoplasm as the organism grows. Simultaneously, many organic foods are oxidized and decomposed in other ways. The energy from the catabolism goes not only to sustain the mechanical and other work of the cell, but also it activates anabolism, which as a whole is endothermic. Moreover, the metabolism of the Amoeba produces a number of waste products which are referred to collectively as the *metabolic* (or excretory) *wastes.*

The metabolic wastes of Amoeba and other animal cells include water, carbon dioxide, simple nitrogenous compounds such as ammonium salts, and a variety of other inorganic salts. Water and carbon dioxide are produced from the oxidation of all organic foods, since hydrogen and carbon are always present in these compounds. Nitrogenous wastes, however, are derived entirely from the decomposition of nitrogen-containing compounds, chiefly the amino acids. Other inorganic salts—such as sulfates and phosphates—result from the decomposition of com-

pounds containing sulfur (e.g., certain amino acids) and phosphorus (e.g., phospholipids), etc.

Respiration. Without oxygen the metabolism of Amoeba and other animal cells may continue for a time, but fatigue begins to set in quickly unless there is a steady supply of oxygen and a continuous disposal of carbon dioxide. *This continuous exchange of gases, in which oxygen enters and carbon dioxide leaves the cell, constitutes the process of respiration.* Unless respiration continues, aside from relatively short interruptions, most cells begin to die of *asphyxiation.*

Unicellular animals do not expend energy in obtaining oxygen, or in disposing of carbon dioxide. In fact, among animals generally, respiration proceeds on an osmotic basis, although higher animals have circulatory fluids, such as blood, which carry O_2 and CO_2 between the cells and the environment. In the Amoeba, however, O_2 and CO_2 are exchanged directly between the protoplasm and the surrounding pond water (see Fig. 56).

Excretion. *Excretion is the process by which metabolic wastes* (excluding carbon dioxide) *are eliminated from the organism.* The excretory wastes (p. 164) are not very toxic, unless they accumulate in the protoplasm, but waste products are produced so constantly during metabolism, that most animals can only survive a few hours if excretion fails to occur.

Except for water, the excretory wastes of Amoeba and other one-celled animals are eliminated by *osmosis.* Owing to metabolism, such wastes as ammonium salts and other salts reach a higher concentration inside the cell than outside. Accordingly these waste products pass out to the environment spontaneously. But the Amoeba is forced to expend energy to eliminate water, since the protoplasm is distinctly hypertonic to the surrounding pond water. The total quantity of water eliminated by the contractile vacuole represents the sum of two parts: (1) the larger part, which constantly enters the cell by osmosis from the hypotonic outside medium, and (2) the smaller part, which is produced metabolically from the oxidation of hydrogen compounds in the protoplasm.

In higher animals the blood stream serves as an intermediary in excretion as well as in respiration. The metabolic wastes pass into the blood from the cells all over the body, and are carried to the kidneys, or other excretory organs, where excretion finally occurs.

The Metabolic Reactions of Animal Cells. All typical animals, regardless of their size and complexity, exhibit the same eight fundamental nutritive processes. In fact the pattern of holozoic nutrition is co-extensive with the animal kingdom, since it depends upon the *kind of metabolism* which characterizes the animal cell. The metabolic enzymes of animals are generally similar, although many specific differences have arisen in the course of evolution. In short, similar enzymes and similar metabolic processes have been inherited by practically all members of the animal kingdom.

Constructive Metabolism. *Protein synthesis.* A very vital problem faced by every cell is the synthesis of protein. To grow and reproduce, or even to support its other activities, each cell must maintain and extend its protein structure—which generally accounts for about 15 per cent of the weight of the cell.

For protein synthesis, animal cells (but not plant cells) must absorb an adequate quantity and variety of *pre-formed* amino acids. Thus each animal must include in its diet at least a minimum of protein food, although this protein cannot be absorbed as such. The protein is first digested, and the resulting amino acids are absorbed and distributed to every cell. Then each cell synthesizes its own proteins, by *dehydration synthesis.*

The proteins synthesized in the cells are not identical to the proteins ingested by the animal. Each cell builds only such specific proteins as are characteristic of its own structure: the protein components of its own pellicle, its own genes, enzymes, and so forth. Most protein foods yield a full assortment of the different amino acids, and consequently one type of protein in the food can usually be substituted for another. The Amoeba, for example, can thrive upon the proteins of a variety of small plants and animals. It may feed predominantly on one species during one season, and on a different species during another—depend-

ing upon abundance. But since the proteins of the different species, when digested, give the same variety of amino acids, all are effective in sustaining the Amoeba.

The cells of most animals can synthesize a few of the amino acids, but these *non-essential* amino acids are all relatively simple, compared to the *essential amino acids*, which must be pre-synthesized by plants (p. 176).

Fat synthesis. Animal cells form fats by dehydration synthesis, from glycerol and fatty acids absorbed from the digestive cavity. Animals also get fat from their carbohydrate and protein foods, although the chemical processes by which glucose and amino acids are transformed into fat are not understood very completely at the present time.

Carbohydrate synthesis. Glycogen, which is the most characteristic polysaccharide in animal cells, is formed by dehydration synthesis from absorbed glucose. Large stores of glycogen are deposited in the liver and muscles of man and other higher animals, from glucose brought to the tissues by the blood stream. The glycogen reserves in animal cells can also be replenished from fats and proteins, but just how these complex transformations occur remains largely a matter of speculation.

In addition to essential proteins, carbohydrates and lipids, many animal cells synthesize a variety of other organic compounds, such as hormones (Chap. 21), which are essential in particular cases. These special syntheses, however, belong to the field of biochemistry. Animals cannot synthesize *vitamins* (Chap. 17), and consequently the vitamin compounds must be present, as such, in the daily diet. The initial synthesis of vitamins occurs in plants, and this is another instance of the dependence of animals upon the synthetic capacities of plants.

The growth of protoplasm implies more than the synthesis or direct acquisition of essential component substances. The substances must be organized and oriented in relation to the protoplasmic structure—a process which is vaguely referred to as assimilation. Also some components of protoplasm are still unknown, such as compounds formed from *trace elements* (like

copper and manganese), which are needed by cells in exceedingly small amounts.

Destructive Metabolism. The principal organic substances absorbed by *animal* cells are simple sugars, glycerol, fatty acids, and the amino acids. All these high-potential compounds are capable of liberating energy (p. 96). The decomposition of organic compounds in the protoplasm involves a variety of chemical processes, as step by step energy is liberated for the use of the cell; and among these catabolic processes, oxidation reactions are of prime importance.

Oxidations. The over-all oxidation of an organic compound, such as glucose, may be stated very simply by specifying the initial and end-products of the reaction, e.g.:

$$\underset{\text{glucose}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2} \rightarrow \underset{\text{water}}{6H_2O} + \underset{\text{carbon dioxide}}{6CO_2} + E \text{ (Energy)}$$

Such an equation merely shows that when decomposition is complete, all the hydrogen of the original compound has united with oxygen, forming water, and all the carbon has been liberated as carbon dioxide. Nothing is shown of the complex intermediary stages which, in the cell, are of great importance. At each step energy is liberated, and each quantity of energy becomes available for the movements and other activities of the cell.

Oxidation[1] generally involves (1) a *gain of oxygen,* or (2) a *loss of hydrogen,* or (3) both—as may be seen in the following example:

$$\underset{\text{ethyl alcohol}}{CH_3 \cdot CH_2OH} + O_2 \rightarrow \underset{\text{acetic acid}}{CH_3 \cdot COOH} + H_2O$$

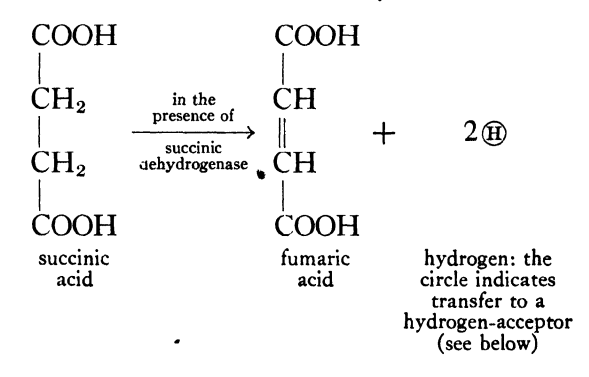
The oxidation of alcohol to acetic acid actually represents a double oxidation. The alcohol not only loses two atoms of hydrogen, but it also *gains* an atom of oxygen, as it is transformed into acetic acid.

[1] Oxidation and reduction are also defined in terms of the losing or gaining of electrons, i.e., oxidation occurs when a substance loses an electron, and reduction occurs when a substance gains an electron.

Likewise the oxidation of alcohol illustrates another general fact. Each time one substance is oxidized, another substance is always *reduced*. Reduction is just the opposite to oxidation, in that *reduction involves either the gaining of hydrogen or the losing of oxygen*. Simultaneously as the alcohol is oxidized, a molecule of O_2 itself is reduced. The O_2 molecule loses an atom of oxygen to the alcohol, and the remaining oxygen atom gains two hydrogens from the alcohol. Accordingly it must be recognized that oxidation and reduction are always simultaneous mutually dependent processes: the problem of how protoplasmic substances are oxidized cannot be separated from the problem of how other substances in the protoplasm are simultaneously reduced.

The Dehydrogenases. A very large part of the energy liberated in protoplasmic oxidations comes from the "burning" of the hydrogen of the organic compounds which are being oxidized. In every cell there is a variety of enzymes, the *dehydrogenases*, which catalyze the transfer of hydrogen, either directly to molecular oxygen (O_2), or to other *hydrogen-acceptor* substances, which simultaneously become reduced.

Succinic dehydrogenase will exemplify the dehydrogenases generally. This enzyme has been identified in the tissues of many animals, as well as in bacteria, molds and higher plants. Succinic dehydrogenase acts specifically upon succinic acid; and the enzyme is important because succinic acid is an intermediary product formed in the catabolism of many cells.



Hydrogen-Accepting Enzymes: The Cytochromes. Hydrogen liberated by the dehydrogenases of the cell is seldom transferred directly to molecular oxygen, although union with free oxygen is the eventual destination. Usually the hydrogen is used to reduce one or more other substances in series—and only the last substance is oxidized by free oxygen. At each stage of this succession of oxidation-reduction reactions, energy is liberated for the use of the cell.

All cells contain a group of enzymes, called the *cytochrome* system, which serves to transmit hydrogen from various organic substrates to free oxygen. In most cells the cytochrome system is made up of three separable components (cytochromes a, b and c), although in special cases, one or even two of these enzymes may be absent. The cytochromes are all protein compounds possessing a chemical structure similar to that of hemoglobin, the red pigment of the blood. One atom of iron (Fe) per molecule is characteristic of each of the cytochromes, as is also the case for hemoglobin.

In accepting hydrogen from a donor substance, the cytochrome enzymes become reduced; and as they are reduced, the cytochromes undergo a change of color, which is analogous to the darkening of hemoglobin when deprived of oxygen. The color change of the intracellular cytochromes is not, however, appreciable to the eye, since these pigments are present in the cell in very small amounts. Detection of the change requires the use of a spectroscope. If a spectroscope is directed upon a tissue, it is seen that all the cytochromes become reduced (by transfer of hydrogen from the dehydrogenase system) as soon as the tissue is deprived of oxygen. But when oxygen is readmitted to the tissue the spectra of the oxidized cytochromes are restored. These results indicate that eventually the hydrogen is delivered by the cytochrome system to free oxygen, at which time water is formed as the end-product of the oxidation.

Cytochrome Oxidase. The transfer of hydrogen from the cytochrome system to free oxygen does not occur in the absence of another enzyme, namely *cytochrome oxidase.* This enzyme likewise is an iron-protein compound. If a tissue extract is pre-

pared containing hydrogen donor substances, dehydrogenases and the cytochrome system, but no cytochrome oxidase, it will not consume oxygen from the atmosphere. But if then a sample of cytochrome oxidase is added, the consumption of O_2 will proceed as hydrogen is passed to the oxygen from the reduced cytochromes.

Cytochrome oxidase is very susceptible to inactivation by such poisons as cyanide (e.g., HCN) and carbon monoxide (CO). The very rapid lethal effects (asphyxiation) of these gases in man and other organisms unquestionably are associated with the blocking of cytochrome oxidase in the tissues of the body, although other contributing factors are probably involved.

The total operation of the cytochrome system may be shown as two equations:

1. 2Ⓗ (from succinic acid, or other hydrogen donor) + Oxidized cytochromes → Reduced cytochromes

distinguished spectroscopically

2. Reduced cytochromes + $\frac{1}{2}O_2$ $\xrightarrow[\text{oxidase}]{\text{cytochrome}}$

H_2O + Oxidized cytochrome (+ Energy)

Other Catabolic Reactions. Many other catabolic processes are recognized by biochemists, but only a few of the simplest and most important will be mentioned.

Deamination. The most important usage of amino acids in a cell is for the construction of needed proteins. But animals also derive energy from amino acids, if the quantity absorbed exceeds the constructive requirements. The decomposition of an amino acid always involves the discharge of the amino fraction from the molecule. In man this leads to the formation of urea, but in lower animals the chief nitrogenous wastes are ammonium salts.

The precise reactions of deamination are problematical, although enzymes capable of performing this function have been identified in the liver and kidney tissues of a number of ani-

mals. The behavior of these deaminases indicates that deamination, at least in some cases, represents an oxidative reaction in which a molecule of water participates, and one molecule of ammonia (NH_3) is formed as a by-product. This may be written as follows:

$$\underset{\text{amino acid}}{\begin{matrix} R \\ | \\ CH\cdot NH_2 \\ | \\ COOH \end{matrix}} + H_2O \xrightarrow[\text{amino-acid oxidase}]{\text{in presence of}} \underset{\text{deaminated compound}}{\begin{matrix} R \\ | \\ C{=}O \\ | \\ COOH \end{matrix}} + \underset{\text{ammonia}}{NH_3} + 2Ⓗ$$

The hydrogen liberated in this reaction is passed directly to molecular oxygen, forming hydrogen peroxide ($2H + O_2 \rightarrow H_2O_2$). Accordingly, two somewhat toxic substances, namely ammonia (NH_3) and hydrogen peroxide (H_2O_2), are formed as by-products of deamination; and these by-products are not allowed to accumulate in the protoplasm. The disposal of hydrogen peroxide (H_2O_2), as it is formed within the tissues, depends upon the presence of *catalase*. This enzyme catalyzes the liberation of free oxygen from hydrogen peroxide (see p. 122). In lower animals, the ammonia becomes bound in the form of ammonium salts (e.g., NH_4HCO_3), which form the principal nitrogenous wastes of these organisms.

However, in man and other mammals, the main nitrogenous waste resulting from the catabolism of the amino acids is *urea* (p. 430). This odorless, white, crystalline *solid* is very soluble in water, and may reach fairly high concentrations in the urine, especially when the diet is rich in protein foods.

Decarboxylation. The complete decomposition of an organic foodstuff depends not only upon dehydrogenation and deamination, but also it finally involves a breakdown of the carbon framework of the molecules, which occurs gradually with the discharge of CO_2. One well-recognized reaction which results in the shortening of organic molecules is the process of decarboxylation. Decarboxylation can be exemplified specifically by

the case of pyruvic acid, an organic compound formed in the metabolism of many cells:

$$\begin{array}{c} CH_3 \\ | \\ C{=}O \\ | \\ COOH \end{array} \xrightarrow{\text{carboxylase}} \begin{array}{c} CH_3 \\ | \\ C{=}O \\ | \\ H \end{array} + CO_2$$

pyruvic acid — intermediary product (acet-aldehyde)

Hydrolysis. Hydrolytic reactions (p. 98) occur frequently in catabolism. Hydrolyses are important in the mobilization of glucose from the glycogen reserves of the cell, and in the splitting of stored fat into glycerol and fatty acids. Proteins, once formed in a cell, are seldom hydrolyzed; i.e., animal cells normally sacrifice only *excesses* of *absorbed* amino acids to meet their energy requirements. But during *starvation,* when all reserves of carbohydrate and fat have been exhausted, cells may hydrolyze their structural proteins and use the resulting amino acids for energy. This, however, is only a stopgap procedure. If it continues very long the living structure will be destroyed beyond repair, and the cell is bound to die.

De-phosphorylation. Recent studies indicate that the mechanical energy expended by muscle tissue comes directly or indirectly from the de-phosphorylation of adenosine triphosphate, which has been recognized for many years as an organic compound present in all muscle tissues. The rupturing of phosphate ($—PO_4$) from an organic compound does not always liberate an abundance of energy, but certain phosphate linkages possess an unusually *high energy potential.* Several different *energy rich phosphate linkages* are now recognized, and probably dephosphorylation reactions will prove to be important sources of energy in other tissues, as well as muscle.

Summary. The enzyme system evolved by typical animals is *not* capable of synthesizing proteins, carbohydrates and the other organic components of protoplasm *solely* from inorganic substances. Therefore, animals must obtain a constant supply of

the case of pyruvic acid, an organic compound formed in the metabolism of many cells:

$$\begin{array}{c} CH_3 \\ | \\ C{=}O \\ | \\ COOH \end{array} \xrightarrow{\text{carboxylase}} \begin{array}{c} CH_3 \\ | \\ C{=}O \\ | \\ H \end{array} + CO_2$$

pyruvic acid — intermediary product (acet-aldehyde)

Hydrolysis. Hydrolytic reactions (p. 98) occur frequently in catabolism. Hydrolyses are important in the mobilization of glucose from the glycogen reserves of the cell, and in the splitting of stored fat into glycerol and fatty acids. Proteins, once formed in a cell, are seldom hydrolyzed; i.e., animal cells normally sacrifice only *excesses* of *absorbed* amino acids to meet their energy requirements. But during *starvation*, when all reserves of carbohydrate and fat have been exhausted, cells may hydrolyze their structural proteins and use the resulting amino acids for energy. This, however, is only a stopgap procedure. If it continues very long the living structure will be destroyed beyond repair, and the cell is bound to die.

De-phosphorylation. Recent studies indicate that the mechanical energy expended by muscle tissue comes directly or indirectly from the de-phosphorylation of adenosine triphosphate, which has been recognized for many years as an organic compound present in all muscle tissues. The rupturing of phosphate ($—PO_4$) from an organic compound does not always liberate an abundance of energy, but certain phosphate linkages possess an unusually *high energy potential.* Several different *energy rich phosphate linkages* are now recognized, and probably dephosphorylation reactions will prove to be important sources of energy in other tissues, as well as muscle.

Summary. The enzyme system evolved by typical animals is *not* capable of synthesizing proteins, carbohydrates and the other organic components of protoplasm *solely* from inorganic substances. Therefore, animals must obtain a constant supply of

lism. In short, it is the possession of a different set of enzymes, among which the green pigment *chlorophyl* is the keystone, which enables plants to base their metabolism entirely upon inorganic forms of matter.

TEST QUESTIONS

1. Define each term in such a way that it will apply to the nutrition of man *and* Amoeba: (a) ingestion; (b) digestion; (c) egestion; (d) absorption; (e) distribution; (f) metabolism; (g) excretion; (h) respiration.
2. Define the term *food;* explain why glucose is considered as a food among animals, but not among plants.
3. How would you account for the fact that a digestive system is generally found in animals, but not in plants?
4. Explain the similarities and differences between Amoeba and Paramecium, in regard to: (a) ingestion; and (b) egestion.
5. Clearly distinguish between egestive and excretory wastes: (a) in animals generally; (b) in Amoeba; and (c) in man.
6. *Chemically* speaking, what is the nature of digestion? Specify the end-products produced as a result of the digestion of: (a) starch; (b) protein; (c) fat; (d) sucrose; and (e) maltose.
7. The absorption of glucose (and the other end-products of digestion) proceeds by osmosis. Carefully explain.
8. In the Amoeba, respiration is an osmotic phenomenon. Explain in detail.
9. To what extent (if any) does the passage of substances into the contractile vacuole of an Amoeba proceed on an osmotic basis? Explain carefully.
10. Distinguish between constructive and destructive metabolism, using the terms exothermic, endothermic, decomposition, and synthesis.
11. Specify the most direct method used by animals in synthesizing: (a) polysaccharides; (b) fats; and (c) proteins.
12. Are there any indirect methods by which an animal can synthesize: (a) polysaccharides; (b) fats; and (c) proteins? Explain carefully.
13. Write an equation which differentiates between oxidation and reduction. Explain the differences carefully.

14. Explain the general importance of the oxidative metabolism of the cell.
15. Identify and exemplify each of the following types of metabolic enzymes: (a) dehydrogenase; (b) the cytochromes; (c) oxidase; (d) carboxylase; and (e) catalase.
16. In protoplasmic oxidations, much of the energy comes from the "burning" of hydrogen. Carefully explain this statement.
17. HCN produces an asphyxiation of most cells. Explain.
18. How do animals differ from plants as to the *primary* source of their energy?

FURTHER READINGS

1. *Biology of the Protozoa*, by Gary N. Calkins; New York, 1933.
2. *The Metabolism of Living Tissues*, by Eric Holmes; Cambridge (England), 1937.
3. *Outline of the Amino Acids and Proteins*, by Melville Sahyun; New York, 1944.

CHAPTER 8

PLANT CELLS AND THEIR NUTRITION

AT LEAST some of the cells of every *typical* plant contain the green pigment, *chlorophyl.* This important enzyme enables the plant to utilize sunlight as a source of energy for sustaining its metabolic processes. Possessing chlorophyl, and having access to light, plant cells are able to synthesize organic matter from *carbon dioxide* and *water.* This process of *photosynthesis* is of the utmost significance. Photosynthesis represents the *ultimate* origin of virtually all organic matter, and the organic compounds derived directly and *indirectly* from photosynthesis contain a large proportion of the energy which sustains life, not only in plants, but also in animals.

Nutrition among green plants is much simplified by the fact that a plant does not need to acquire any *pre-formed* organic foods. The complete list of essential plant foods includes only water, carbon dioxide, various inorganic salts and oxygen. All these foods are simple crystalloidal substances, present practically everywhere, and consequently they can be absorbed *directly from the environment.* Thus plants generally do not possess any digestive system, and the *holophytic mode of nutrition* does not include any processes of *ingestion, digestion,* and *egestion.* Accordingly nutrition in typical plants begins with the process of *absorption.*

Absorption in Unicellular and Colonial Plants. Virtually all simple *green* plants, which lack root, stems, and leaves, are designated collectively as the *algae.* Many of the algae, such as Closterium and Chlamydomonas (Fig. 63), are unicellular, but some, such as Spirogyra (Fig. 64) are colonial, and others, such

as Nitella (Fig. 127), are true multicellular organisms. Algae differ from the simple animals in that they all possess chlorophyl, and most have relatively thick, rigid *cell walls*. Usually the chlorophyl is localized within well-defined chloroplasts, of

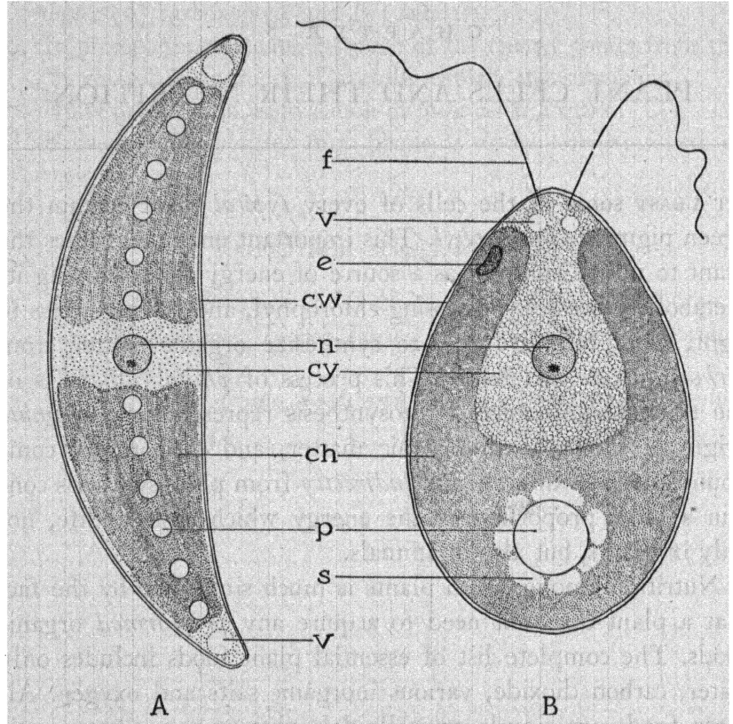
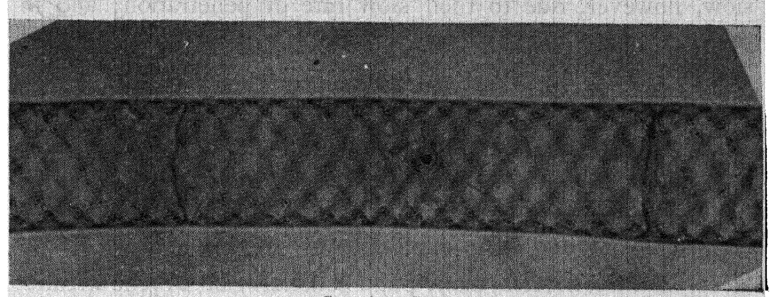


FIG. 63.—Unicellular green algae; A, Closterium; B, Chlamydomonas. n, nucleus; cy, cytoplasm; ch, chloroplast; p, pyrenoid; s, starch grains; v, vacuole; cw, cell wall; f, flagellum; e, red pigmented "eye spot."

which one or more may be present in each cell. Sometimes the green color of the chlorophyl is masked by the presence of other pigments, as in the case of brown and red algae. Most algae differ from Protozoa in having no means of locomotion, although some species possess one or more highly motile, whip-like *flagella* (Fig. 63, B).

Algae, in contrast to most higher plants, are essentially *aquatic* plants. A few dwell in very moist places on the land, as for example, Protococcus (Fig. 65), which may be found on

tree-trunks, in the damp crevices of the bark. But most algae grow under water. Closterium, for example, is a unicellular form very commonly found in fresh water ponds and lakes.



Copyright General Biological Supply House, Chicago

FIG. 64.—One cell in a filament of the green alga, Spirogyra. The nucleus, with a distinct darkly stained nucleolus, lies at the center, suspended in place by delicate strands of cytoplasm. The chloroplast has the form of a spiral ribbon, on which numerous small stained bodies, the pyrenoids, are discernible.

The problem of absorption in a submerged unicellular plant such as Closterium (Fig. 63, A) is not very acute. All essential nutrients are right at hand, dissolved in the surrounding medium; and all the food substances can enter the cell by osmosis through the plasma membrane. Fresh water, essentially, is a very hypotonic solution. The main solutes are inorganic salts—

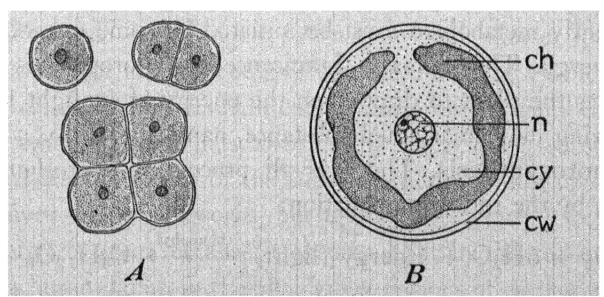


FIG. 65.—Protococcus, a unicellular green plant. A, temporary aggregates of cells, as they occur naturally. B, a single cell, more highly magnified, stained and sectioned. n, nucleus; cy, cytoplasm; ch, chloroplast; cw, cell wall.

which dissolve in rain water as it seeps through the soil and collects in the pond—together with the atmospheric gases, carbon dioxide and oxygen. All of these substances pass into the

cell spontaneously. As they are used up by the cell in metabolism, each substance is replaced from the environment, mainly on an osmotic basis. The absorption of the inorganic salts is very slow, however, due to their slow rate of penetration; and in some cases, there is evidence that plant cells resort to special energy-consuming processes to accelerate and augment the absorption of salts.

Distribution. In unicellular plants such as Closterium, the distribution of absorbed food substances throughout the protoplasm is just as simple as in one-celled animals (p. 155). Once within the plasma membrane, the different nutrients diffuse freely in the cell. Also, many plant cells carry on a cyclic streaming (cyclosis, p. 217) of the protoplasm, and this assures a more rapid equilibration of absorbed substances.

The problem of absorption and distribution in the larger land plants is somewhat more difficult. In such forms, the root system accomplishes practically all absorption, since the roots are the only parts that lie in contact with the soil water. The water and salts absorbed by the roots are then carried in special vessels throughout the stem and leaf systems, which in some plants reach hundreds of feet above ground.

Constructive Metabolism in Green Plant Cells. No fuels are included among the foods absorbed by the plant and consequently metabolism must be initiated by some outside source of energy. The primary significance of chlorophyl is that it enables the plant to draw upon the energy of sunlight for synthesizing its primary fuel substance, namely *glucose.*

Photosynthesis. The over-all process of photosynthesis is given by the following equation:

$$6CO_2 + 6H_2O + \text{Energy (light)} \xrightarrow{\text{chlorophyl}} C_6H_{12}O_6 + 6O_2$$

Or, stated in words, chlorophyl enables the plant cell to utilize light energy in synthesizing glucose and oxygen from carbon dioxide and water.

The quantity of energy stored up by the plant as a result of photosynthesis amounts to 4 Calories per gram of glucose, i.e., exactly the quantity which is liberated when glucose undergoes

oxidation. In short, photosynthesis transforms light energy, which is otherwise quite useless as a source of vital energy, into a useful form of potential energy (glucose and oxygen) which becomes available to living organisms generally.

The photosynthetic formation of glucose and free oxygen has great importance in the total economy of life. Were it not for the fact that the green plants continuously form oxygen and return it to the atmosphere, the supply of this essential atmospheric gas, tremendous though it is, would long ago have been depleted. Also the large supply of glucose, created by green plants generally, is drawn upon, directly or indirectly, by all organisms, as a source of matter and energy for their life and growth. Without photosynthesis, evolution could not have given rise to such a wide variety of living forms as exist today.

To understand the role of chlorophyl in photosynthesis, it is necessary to know something about how substances absorb light, and how the absorption of light promotes chemical reactivity. If a beam of ordinary white light (e.g., sunlight) is passed through a triangular glass prism, it is broken up into a series of colors, arranged in a regular order—red, orange, yellow, green, blue, violet—called a *spectrum* (Fig. 66). Of these colors, the red consists of the longest light waves and the violet of the shortest waves. Beyond these two ends of the visible spectrum, there are still longer (infra-red) and shorter (ultra-violet) waves of radiant energy; but these are not visible, and are not called "light." Radiant energy can promote many chemical reactions, provided it is *absorbed* by the reacting substance, or substances. The color of the substance depends, not upon the light waves which it absorbs, but upon those which it reflects. Chlorophyl is green because it absorbs light in the red-orange and, to a lesser extent, in the blue-violet regions of the spectrum. The greatest *quantity* of energy in sunlight as it reaches the earth is in the red-orange part of the spectrum, where absorption by chlorophyl is maximum. This means that a relatively large proportion of the light energy impinging upon chlorophyl is available for transformation into potential energy—the

potential energy which resides in the molecular structure of glucose and oxygen.

The photosynthesis reaction is sharply focalized in the chloroplasts of the plant cell. Carbon dioxide and water are used up as photosynthesis proceeds, and consequently these substances continually pass to the chloroplasts along the diffusion gradient

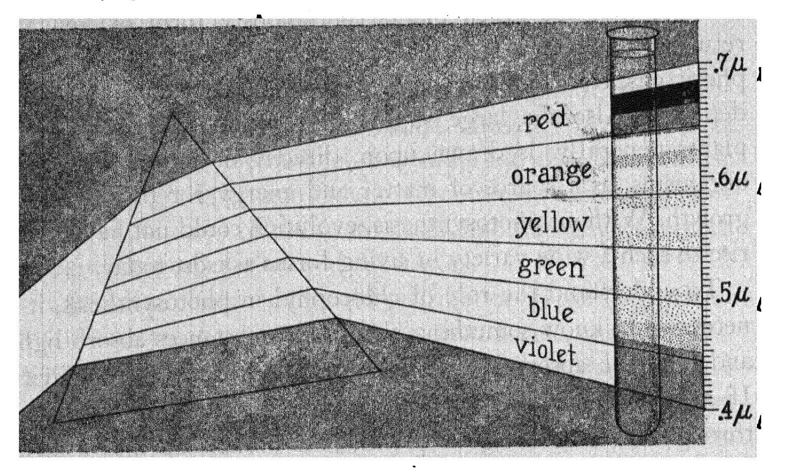


FIG. 66.—A beam of sunlight passed through a glass prism, which disperses the light, forming a spectrum, and then through a test tube containing a solution of chlorophyl, which absorbs light in certain regions of the spectrum; the relative intensity of this absorption is indicated by the depth of shade in the absorption spectrum at the right. The scale at the right shows the wave lengths of the light in each region of the spectrum. (Adapted, in part, from Ganong.)

which is established. And since glucose and oxygen continually result from photosynthesis these end-products tend to escape from the chloroplasts. The precise intermediary stages involved in the conversion of carbon dioxide and water into glucose and oxygen are not clearly understood. Apparently the mere extraction of chlorophyl from the cell disrupts the pigment from some essential association with the protein components of the cytoplasm, and consequently the extracts display little or no enzymatic activity.

Recent studies prove that plants utilize light energy not to reduce carbon dioxide, but to decompose water; and subsequently the liberated hydrogen and oxygen are used in other metabolic

reactions, which proceed in the absence of light. It is possible to keep track of the carbon dioxide utilized in a tissue. By supplying the cells with a specially prepared form of CO_2 in which the carbon is radioactive, the subsequent location of the carbon in the tissue can be ascertained, using an electronic detector. These experiments show that many tissues—in animals as well as plants—can reduce CO_2, affixing the carbon to some organic substrate (S). Such a reaction can occur in the complete absence of light providing a suitable hydrogen-donor is present to provide the matter and energy; e.g.:

$$\text{Substrate (S)} + CO_2 + Ⓗ \rightarrow \text{S—COOH}$$

Such a fixation of carbon does not represent any net gain of energy, however, since the energy gained by the reduction of the carbon dioxide is more than counterbalanced by the loss of energy suffered by compounds which donate the Ⓗ (p. 161), or by other compounds which are catabolized simultaneously.

In similar manner, specially prepared water, containing only *heavy oxygen* (atomic weight 18, instead of 16), has been used to trace the origin of the free O_2 which is produced during photosynthesis. These experiments show that *all* the oxygen comes from the decomposition of water, which only occurs when light is available. During photosynthesis, apparently, the hydrogen from the decomposing water is picked up by various hydrogen acceptors (p. 162) in the cell, and then used, without benefit of light energy, to reduce carbon dioxide. Moreover, the oxygen from water does not appear to be liberated directly, but first forms a peroxide compound, which later gives off its excess oxygen.

1. $$4nH_2O + \text{Light energy} \rightarrow 4nH + 4nOH$$

2. $$n(4H + CO_2) \rightarrow (CH_2O)n + nH_2O$$

glucose,
or other
carbohydrate

3. $$n(4OH) \rightarrow 2nH_2O_2 \rightarrow 2nH_2O + nO_2$$

peroxide,
or a peroxide
compound

According to these recent studies, the most probable course of the photosynthetic reactions may be represented by the foregoing equations, in which n equals six, or a multiple of six. These equations show: (a) the energy gain comes from the photochemical decomposition of water; (b) carbon dioxide reduction may proceed without light, through the intervention of hydrogen donors in the protoplasm; and (c) the liberated oxygen comes from the photochemical decomposition of water, although an intervening peroxide compound is probably involved.

Other Aspects of Constructive Metabolism in the Green Plant. Closterium and other green plant cells use glucose, after it is photosynthesized, as a source of energy, and also as a source of matter for the synthesis of other organic compounds (proteins, carbohydrates, fats, etc.), which are needed for maintenance and growth.

Protein synthesis. The formation of proteins in plant cells depends upon a preliminary synthesis of the various amino acids. All amino acids can be synthesized by plant cells (but not by animal cells), provided glucose and inorganic salts are available. Glucose provides the plant cell not only with energy for amino acid synthesis, but also with matter, to form the carbon-hydrogen parts of the molecules. But the plant derives nitrogen, sulfur, phosphorus, and other constituents of the amino acids from the inorganic salts.

As a source of the nitrogen, for the amino ($—NH_2$) portions of the amino acids, plant cells cannot draw upon the free nitrogen (N_2) of the atmosphere. But the plant does possess the proper catalytic equipment for using nitrogen in the form of the nitrate salts (e.g., $NaNO_3$, KNO_3, etc.). Similarly the plant requires sulfur (for the synthesis of some of the amino acids) chiefly in the form of the sulfate ($—SO_4$) salts.

The precise manner in which nitrogen is transferred from the nitrate salts to the amino radicals of the amino acids is not known; but given nitrates as a source of nitrogen, green plants enjoy a full measure of growth. The nitrate content of the soil

and of fertilizers is a prime consideration. If the nitrate supply is limited, the formation of amino acids within the plant is reduced—and since new proteins are formed solely by dehydration synthesis from previously formed amino acids, the growth of the plant is likewise limited.

Carbohydrate synthesis. During periods of abundant light, the plant cell produces glucose *in excess* of its current needs. This excess glucose is converted mainly into *starch*, by dehydration synthesis, a reaction which is independent of light. In many plant cells the amylases responsible for starch synthesis are localized in small visible bodies, the *pyrenoids* (Figs. 63 and 64); and consequently starch grains first appear near this part of the cell. Starch represents a reserve of glucose: during periods of darkness starch may be hydrolyzed, yielding an immediate supply of glucose. Cellulose, for the cell walls and other structural parts, is also derived by dehydration synthesis from photosynthesized glucose.

Other syntheses. Some complex proteins contain sulfur, phosphorus and iron, which are derived from the inorganic salts of these elements absorbed by the plant. Like animal cells, plant cells can form fats and other lipids from carbohydrates, although the intermediary stages of these transformations are still unknown.

In general, the synthetic powers in plants are greater and more varied than in animals. Besides synthesizing carbohydrates, fats and all the various amino acids, plants can also synthesize a wide variety of other compounds which animals cannot. Such compounds include not only chlorophyl and other special pigments, but also all the vitamins (p. 438), and many other useful substances, such as drugs, perfumes, etc. Moreover, in producing this wide variety of organic compounds, green plants utilize nothing but inorganic substances which are absorbed from the environment.

Destructive Metabolism. As to destructive metabolism, plant and animal cells are essentially alike. But the metabolism of plants is simpler because plant cells depend almost solely upon *glucose* as a source of energy. The supply of photosyn-

thesized glucose is adequate to balance the energy expenditures of the plant, and consequently other fuels are seldom utilized. In particular, amino acids and proteins are not sacrificed for energy, except under conditions of starvation—as, for example, when a plant is deprived of light for a long period. The plant limits the synthesis of amino acids to its constructive needs, and thus no excesses are available for energy. Moreover, the fats stored in plant cells are ordinarily reconverted to carbohydrates before oxidation occurs.

The energy expended by a plant in destructive metabolism goes mainly to foster constructive metabolism. The plant does not have to move about in search of food and expends less total energy than the animal. In using a lesser proportion of its materials for destructive metabolism, the plant has more available for constructive purposes. Consequently plants in general grow more rapidly than animals.

Respiration in Plants. All plant cells constantly use oxygen and produce carbon dioxide, as a result of oxidative metabolism. But during periods when light is available, the green plant cell produces 15-30 times more oxygen than it uses; and consumes much more carbon dioxide than it produces. Consequently in the daytime respiration (taking in O_2 and giving off CO_2) is overbalanced by the gas exchange of photosynthesis (taking in CO_2 and giving off O_2), which is just the opposite. But in darkness, when photosynthesis is suspended, all plant cells carry on a small but measurable respiration.

Gas exchanges in a simple submerged plant such as Closterium (Fig. 63) proceed on a purely osmotic basis. While carbon dioxide is being used up (by photosynthesis) faster than it is being produced (by oxidative metabolism), the CO_2 concentration in the cell remains lower than in the surrounding water; and while oxygen is being formed faster than it is consumed, the O_2 concentration in the cell remains relatively high. Consequently during periods when light is available the gas exchange of photosynthesis predominates. But when photosynthesis ceases, the concentration of oxygen inside the cell sinks below the level of dissolved oxygen in the outside water; and

the quantity of carbon dioxide rises above that of the environment. Consequently under these circumstances, respiration holds sway.

Excretion in Plants. Very little excretion is necessary in green plants. Plants produce scarcely any metabolic wastes other than carbon dioxide and water—and these end-products are re-used during photosynthesis. In so far as small quantities of other wastes are produced, these likewise may be consumed again in constructive metabolism. To a remarkable extent, therefore, it may be said that plant cells are able to "burn their own smoke." In a few cases, certain plant cells tend to accumulate special waste products, depositing them as insoluble crystals in the protoplasm or vacuoles.

When photosynthesis is in abeyance, carbon dioxide and water tend to accumulate. The carbon dioxide passes off in respiration, leaving water as the sole excretory waste produced in any abundance. In aquatic forms, such as Closterium, this excess water also passes out into the environment. Despite the fact that the surrounding fresh water is very hypotonic, the high turgor of the cell establishes an equilibrium in which the inflow of water is balanced by the outflow. Therefore when additional water is formed by metabolism, the equilibrium is disturbed and the excess water passes to the outside.

General Significance of Holophytic Nutrition. The salient points of contrast between holophytic and holozoic nutrition are summarized in Table X; and the significance of these points cannot be over-emphasized. The holophytic system of enzymes, with chlorophyl as a keystone, enable green plants to tap the tremendous fund of energy which radiates upon our earth from the distant sun. This kinetic energy, transformed into the potential energy of a great variety of organic compounds, represents almost the sole energy supply of all varieties of living things. Animals large and small derive their energy from preformed organic foods, by feeding either directly upon the plants, or upon other organisms which directly or indirectly have obtained their organic matter from the plants. In addition to maintaining the supply of organic matter, light energy also

TABLE X

HOLOPHYTIC AND HOLOZOIC NUTRITIONS CONTRASTED

Green Plant	*Animal*
1. Has chlorophyl—can synthesize glucose	1. Has no chlorophyl—cannot synthesize glucose
2. Can utilize nitrates and other inorganic salts to synthesize amino acids	2. Cannot utilize nitrates to synthesize amino acids
3. Can synthesize all amino acids	3. Cannot synthesize all amino acids
4. Independent of other organisms for organic compounds	4. Dependent on other organisms for organic compounds
5. Absorbs all food in solution	5. Ingests solid food
6. Does not move about for food; expends less energy; less catabolism	6. Moves about for food; expends more energy; more catabolism
7. Primary source of energy is light	7. Only source of energy is organic compounds
8. Metabolism *as a whole* constructive; i.e., increases available organic compounds; increases the reserve of potential energy	8. Metabolism *as a whole* destructive, i.e., decreases available organic compounds; decreases the reserve of potential energy

maintains our oxygen supply, which would be exhausted in about 2,000 years if photosynthesis did not occur. Only a small fraction of the sun's radiance happens to fall upon green plants, and only about 3 per cent of this energy is claimed successfully by photosynthesis. But this small fraction energizes virtually all the manifold processes of life, and this energy is not degraded into heat until it has found expression in the movements and other activities of many living things. Eventually, however, all the solar energy which strikes the earth becomes transformed to heat, and is dissipated in the environment (Chap. 9).

TEST QUESTIONS

1. Most plants are non-motile organisms. Explain this observation in terms of the food requirements of plants.
2. What is the basis for considering that Closterium, Chlamydomonas and Spirogyra are all typical plants?
3. How do the algae differ from most higher plants: (a) as to habitat; and (b) as to general structure?
4. To what extent does absorption in Closterium and other algae depend upon osmosis? Explain.

5. Define the term photosynthesis, specifying precisely the kinds of matter and energy that are involved.
6. One plant is exposed to green light, and another, to red light. Predict the relative rates of photosynthesis in the two plants. Explain.
7. In photosynthesis light energy is utilized not to reduce CO_2, but to liberate hydrogen and oxygen from H_2O. Explain the experiments which substantiate this viewpoint.
8. Can animals and plants utilize CO_2 in the formation of organic compounds? To what extent is light energy involved in such processes?
9. Give equations specifying the various reactions which (probably) are involved in photosynthesis.
10. Explain the general importance of photosynthesis:
    a. from the "viewpoint" of a plant;
    b. from the "viewpoint" of an animal.
11. Give five ways in which glucose may be used in the cells of a typical plant, in each case specifying such chemical reactions as may be involved.
12. Compare animal and plant cells, as regards:
    a. the origin of amino acids utilized in metabolism;
    b. ways in which amino acids are utilized in metabolism.
13. Carefully explain why nitrate ($—NO_3$) salts are plant foods of great importance. Why are sulfates and phosphates likewise needed by green plants?
14. Account for the fact that considerable quantities of nitrogenous wastes are formed in the metabolism of animals, but not in the metabolism of plants.
15. Construct a table showing the main points of contrast between the holophytic and holozoic types of nutrition.
16. Point out five essential similarities between the holozoic and holophytic types of nutrition.

FURTHER READINGS

1. *Soilless Culture Simplified*, by Alex Laurie; New York, 1940.
2. *The Plant World*, by Harry J. Fuller; New York, 1941.

CHAPTER 9

OTHER MODES OF NUTRITION; CONSERVATION OF THE FOOD ELEMENTS

ALMOST all higher organisms are either typical animals or typical plants; but among lower organisms, the lines of distinction are somewhat blurred. Among lower organisms, some are holophytic, some are holozoic, others are more or less intermediate between the plants and the animals, and still others are quite different, as to their nutrition, from either plants or animals.

The Fungi. The *fungi* are a large group (about 75,000 species) of relatively *simple plants which do not possess chlorophyl.*

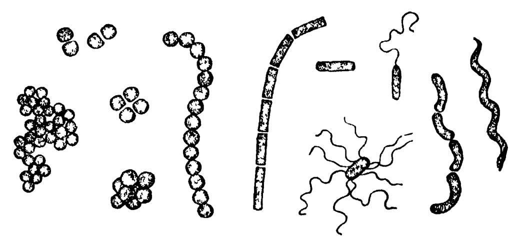


FIG. 67.—Several types of Bacteria. The spherical forms are cocci; the rod-shaped forms, bacilli; and the spiral forms, spirilla. Colonial aggregates of bacteria are designated by special names; e.g., staphylococcus, for irregular bunches of cocci, like those on the left; and streptococcus, and streptobacillus, for the chainlike colonies of cocci and bacilli (shown at the center).

In general the fungi possess cellulose cell walls, and they lack the capacity to *ingest* food. Because of these characteristics, and because they closely resemble the algae in their general structure and reproductive habits, the fungi are classified as plants, despite their lack of chlorophyl.

Many fungi, including the *bacteria* (Fig. 67) and *yeasts* (Fig. 68), are unicellular; but others, including the *molds,*

mildews, *rusts*, *smuts*, *puffballs* and *mushrooms*, are more complex in structure. The body, or *mycelium*, of a complex fungus consists of a mass of long, slender, much-branched threads, called *hyphae*. In some species the mycelium displays a syncytial organization; in others it consists of distinct cells, individually separated by transverse cell walls (Fig. 69).

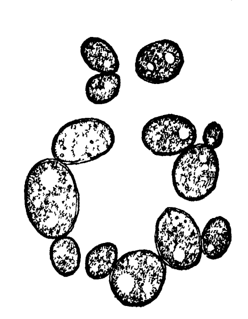


Fig. 68.—Yeast cells. The light spots are fat droplets and cell-sap vacuoles; the nuclei are not visible in the living, unstained cells.

Saprophytic Nutrition. This mode of nutrition is displayed by most of the yeasts, molds and bacteria. Saprophytic organisms, like animals, require at least a minimum of pre-formed organic food; but lacking a digestive cavity, saprophytes must *absorb* their *organic nutrients directly from the environment*. Therefore the localities favorable for the growth of saprophytes are very limited. Such forms are found only in places where considerable quantities of organic materials have accumulated, such as upon soil richly laden with humus (decomposing plant material), or directly upon the remnants of other organisms.

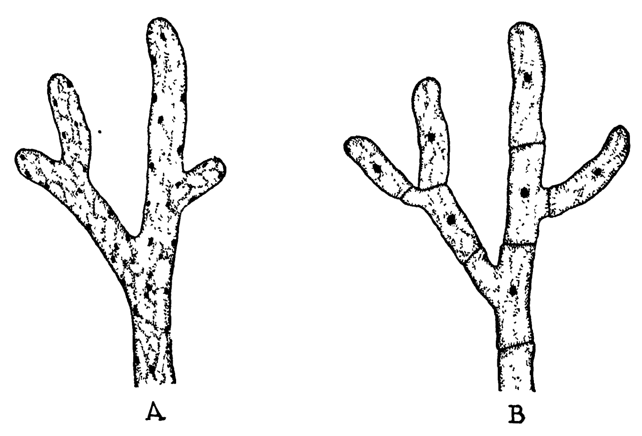


Fig. 69.—Small portions of the mycelia of two common mold fungi; A, Mucor; B, Aspergillus. The black spots are nuclei.

Nutrition of Yeasts. Many wild yeasts grow saprophytically upon sweet fruits which have been crushed in falling to the ground. The most important yeasts, however, are the kinds which are cultivated by man because of their usefulness in brewing and in bread-making (Fig. 68).

Yeast *cannot* grow like a *green* plant in a medium containing only inorganic substances. But yeast will thrive vigorously in a solution containing sugar (glucose, sucrose or maltose), oxygen and a suitable variety of inorganic salts. Lacking chlorophyl, the yeast cannot synthesize its own sugar, but given "ready-made" sugar as a source of energy and matter, it can carry on metabolism quite like a green plant. Like the green plant it can utilize inorganic nitrogen to synthesize all essential amino acids and proteins, although yeasts grow better when ammonium (NH_4^+) salts, rather than nitrates (NO_3^-), are available.

When glucose is present in the surrounding medium, the yeast absorbs the sugar directly, without recourse to any sort of digestive process. But when the available sugar is a disaccharide, such as sucrose (or maltose), digestion must precede absorption. In this case, the enzyme *sucrase* (or *maltase*) is extruded from the yeast cells, and *digestion occurs externally*, in the surrounding medium. Starch cannot always be used as a source of glucose, because the *digestive* enzymes of the yeast do not include any *amylase*. However, ground malt (germinated barley) is usually added to a yeast brew, and the amylase from the barley cells serves to hydrolyze the starch to glucose.

Anaerobic Metabolism of Yeast. In the presence of adequate oxygen, yeast cells, like plants and animals generally, obtain energy by oxidizing carbohydrates and other compounds. But when free oxygen is scarce or lacking, the yeast replaces this *aerobic metabolism* by an *anaerobic metabolism*. Under these conditions the yeast obtains energy by *alcoholic fermentation*, and this decomposition of glucose into ethyl alcohol and carbon dioxide does not require the utilization of oxygen:

$$\underset{\text{glucose}}{C_6H_{12}O_6} \xrightarrow{\text{zymase}} \underset{\text{ethyl alcohol}}{2C_2H_5OH} + \underset{\text{carbon dioxide}}{2CO_2} + \text{Energy (about } 1/5 \text{ Cal. per gm. of glucose)}$$

Owing to the fact that the non-oxidative metabolism of glucose yields only about 1/20 as much energy as the oxidative metabolism, yeast grows much more slowly and less efficiently under anaerobic conditions. Moreover, the metabolic wastes, especially alcohol, tend to accumulate in the medium after escaping from the cells by osmosis; and the alcohol finally exerts a toxic effect, despite a unique tolerance which yeasts have developed to this compound. But the possession of *zymase*, a complex of enzymes which catalyzes alcoholic fermentation, enables the yeast to *survive* for quite a long period under anaerobic conditions such as are lethal to most other organisms.

The importance of yeast in human economy is due to the fact that fermentation constitutes the only practical source of alcoholic beverages, and of ethyl alcohol, which is widely used as a solvent and raw material in chemical industry. In the brew-mashes of beers and wines, most of the alcohol is formed by the dense population of yeasts near the bottom of the brew-tank. Near the top of the tank, which is more or less open to the atmosphere, there is ample oxygen, and the yeasts of this region produce little or no alcohol. But the oxygen is soon used up at the bottom of the tank, and new oxygen entering from the atmosphere is consumed by the upper layers of yeasts before it can diffuse to the bottom layers. The proportion of alcohol in a natural brew never exceeds about 12 per cent, since this is the maximum tolerable to the yeasts themselves. However, by distillation the proportion of alcohol may be increased up to 95 per cent. In bread-making, the alcohol produced in dough is unimportant, since the relatively small quantity is dissipated during baking. But the carbon dioxide forms bubbles which are trapped in the thick dough mixture, and this "raises" the dough, giving a porous texture to the bread.

Nutrition in the Bread Mold. The spores of the bread mold (*Rhizopus nigricans*) are abundant in the atmosphere, especially in populated regions. Consequently an exposed piece of moist bread or other starchy food almost invariably becomes covered by the fuzzy white mycelium of the bread mold. Later this

growth turns blackish-gray, indicating that a new crop of spore capsules has become ripe.

The *mycelium* of the bread mold is composed entirely of a mass of much-branched threads, or *hyphae*, which are of three sorts: (1) short, clustered *rhizoids*, which penetrate down into the substance of the bread; (2) long, stout *stolons*, which form an interlacing mass over the surface of the bread; and (3) long, slender *sporangiophores*, which extend vertically upward, each supporting a single *spore capsule* at its upper end (Fig. 96).

The bread mold, which is a typical saprophyte, uses starch as its main organic food. Starch cannot be absorbed as such, but the rhizoids of the mold secrete *amylase* into the surrounding bread or other food material. Thus *digestion* occurs externally, and the resulting glucose passes by osmosis into the rhizoids. The rhizoids serve also for the *absorption* of the other essential nutrients, including water, salts and oxygen. The *distribution* of the food substances proceeds by diffusion and protoplasmic streaming, via the rhizoids to the stolons, and via the stolons to the sporangiophores. The *metabolism* of the mold closely resembles that of the yeast, except that anaerobic growth does not occur. Also the mold (to a greater extent than yeast) utilizes nitrate ($—NO_3$) salts for the synthesis of essential amino acids and proteins. All energy is derived from pre-formed organic substances (chiefly carbohydrate) which are absorbed. Respiration and excretion are localized mainly in the rhizoids, since the upper parts of the mycelium are too dry to permit osmotic exchanges with the air. The only significant excretory waste is water, since carbohydrate is the main fuel.

Economic Importance of the Yeasts and Molds. A wide variety of yeasts and molds have been known to biologists for many years, and investigations on the metabolism of these organisms have gradually revealed a number of by-products which are very important in medicine and industry. More than 100,000 tons of yeasts are produced annually in the United States, and various kinds of fermentation are used in the production of citric acid, glycerol, acetone, purified fats, and a number of other valuable organic compounds. Likewise yeasts are widely used in

the production of vitamins, and massive yeast cultures are beginning to be used as direct sources of man's food. Among the molds, Penicillium is of primary importance as a source of *penicillin*, which counteracts many stubborn bacterial infections; and several other molds have important uses in the curing of hides, tobacco, coffee, cocoa, paper pulp, etc. Moreover, yeasts and molds frequently play accessory roles in processes which are effected primarily by the saprophytic bacteria (see p. 188 f.).

Nutrition in the Saprophytic Bacteria: Decay and Putrefaction. Although bacteria are among the smallest and, from the viewpoint of visible structure, the simplest of all organisms, they display a remarkable diversity in their nutritive processes. Among the saprophytic forms, which constitute a large majority of the bacteria, many variations exist as to the chemical nature of the organic substances required by the different species for the fulfillment of their metabolic needs.

Bacteria lack chlorophyl, although one small group, the purple bacteria, possess a chlorophyl-like pigment, and utilize light to accelerate—but not to *energize*—their metabolic processes. Bacteria possess relatively rigid cell walls, composed of organic substances other than cellulose. Accordingly, it is upon rather arbitrary grounds that the bacteria are classified among the plants.

Although the nutritional variation among bacteria is very great, the variation in form is generally limited to three common shapes. Among bacterial species there are: (1) spherical forms, called *cocci*, (2) rod-shaped forms, called *bacilli*, and (3) spiral forms, called *spirilla* (Fig. 67). Many bacteria are strictly unicellular, but others form colonial aggregates of greater or lesser permanence; and bacterial colonies are usually named according to the arrangement of the cells in the aggregate. Irregular clusters are designated by the prefix *staphylo-*, as in staphylococcus; and chainlike forms are specified by the prefix *strepto-*, as in *streptococcus*, or *streptobacillus*.

The great importance of saprophytic bacteria is that their digestive and metabolic processes effect the decomposition of a vast quantity and a rich variety of organic materials which other-

wise would tend to accumulate on earth in a form not suitable for the use of other organisms. Without the saprophytic bacteria all decay would be eliminated, except for that relatively small fraction which results from the nutrition of other saprophytes (e.g., yeasts and molds).

Decay and Putrefaction. The saprophytic bacteria are all spore-formers (p. 61), and bacterial spores are abundant everywhere except in the purest atmospheres. Consequently whenever a mass of organic material, such as a dead body or other organic remnant remains exposed, bacterial spores fall upon it and begin to grow. In their nutrition, the saprophytic bacteria utilize the various organic substances present in the original material, decomposing these compounds eventually into simple inorganic end-products; and this process as a whole is designated as *decay*.

Many different bacteria participate in decay, and each species is very specific as to the organic substances it utilizes as food. Some grow on carbohydrates: like the *cellulose bacteria*, which use the enzyme *cellulase*, to digest woody materials and obtain glucose; and the *milk souring bacteria*, which absorb lactose and convert it (anaerobically) into *lactic acid* ($CH_3 \cdot CHOH \cdot COOH$); and the *vinegar bacteria*, which oxidize alcohol (present in hard ciders or wines) into *acetic acid* ($CH_3 \cdot COOH$). Other bacteria possess different enzymes, which enable them to grow on fatty substances. Thus, the smell of rancid butter is due mainly to *butyric acid* ($C_3H_7 \cdot COOH$), produced by the action of certain bacteria upon butter fat.

The total decay of *protein* material is designated by the special name of *putrefaction*. Putrefaction involves the growth of a variety of saprophytic bacteria, which act simultaneously and successively upon the protein, until nothing but inorganic end-products remain. During the intervening stages, however, a number of foul-smelling and toxic substances (e.g., various *organic amines* and *ptomaines*) are formed in the metabolism of some of the species, but these substances are finally absorbed and utilized by other species.

The liberation of the inorganic compounds of nitrogen, which results from the bacterial decomposition of proteins and other organic nitrogen compounds, is very important in relation to soil fertility. Some saprophytic bacteria utilize urea [$CO(NH_2)_2$], hydrolyzing this compound into ammonia (NH_3) and carbon dioxide (CO_2), which pass forth into the environment. The nitrogen of proteins and other complex nitrogenous compounds is likewise liberated by the putrefactive bacteria chiefly in the form of ammonia, although small quantities of free nitrogen (N_2) are produced by some species. Free nitrogen is also liberated by the burning (in fires) of organic nitrogen compounds, and in greater quantities by the *denitrifying bacteria.* These soil bacteria utilize carbohydrates present in decaying humus. When the soil is well aerated by cultivation, the denitrifying bacteria depend upon free oxygen for the oxidation of their carbohydrates. But when free oxygen is lacking, they decompose nitrate ($—NO_3$) salts, using this bound form of oxygen instead; and under these circumstances the denitrifying bacteria liberate *free nitrogen.* The liberation of *free* nitrogen from various nitrogen compounds represents a definite loss of soil fertility, because green plants are not able to use free nitrogen to sustain their growth.

In summary, the *complete* decay of any material involves a series of different bacteria acting successively upon the various organic substances as they appear in the decomposing mass. Some of the decomposition reactions are digestive, and others are metabolic in nature—but the final end-products are all simple inorganic substances. The carbon of organic compounds emerges from the process mainly as CO_2, and the hydrogen mainly as H_2O. The nitrogen part of various organic compounds appears chiefly as NH_3, although small quantities of N_2 and of nitrate ($—NO_3$) salts may be formed. Other elementary constituents (S, P, etc.) are also finally converted to inorganic form (chiefly $—SO_4$, $—PO_4$, etc.).

The processes of decay are very important in the general economy of life. Without decay, including putrefaction, significant quantities of the inorganic substances necessary for the

growth of green plants would not be returned to the soil and air. Man also makes use of a number of saprophytic bacteria: in tanning leather, curing tobacco, making cheese, and disposing of sewage. All in all, the benefits which accrue from the saprophytic bacteria far outweigh the harm done in the spoiling of foods and other valuable materials. Many methods have been developed to *preserve* foods from the action of bacteria; refrigeration retards their digestive and metabolic processes; salting plasmolyzes the cells; dehydration deprives them of adequate water; chemicals kill them; and above all, canning prevents the bacteria from regaining access to food after they have been killed by *heat-sterilization.*

Mixotrophic Nutrition. *Mixotrophic* organisms are those which can carry on more than one mode of nutrition. For example, *Euglena* (Fig. 70) and any other *green flagellates,* can live like typical plants, when *light* is available; but these organisms can also grow saprophytically. Euglena resembles a one-celled animal—in having a mouth and gullet, in its ability to propel itself through the water, and in lacking a rigid cellulose cell wall. But also Euglena is like a plant, in that it possesses *chloroplasts* which enable it to carry on photosynthesis. Likewise Euglena stores its excess glucose in the form of starch, and utilizes nitrate (—NO_3) salts for the synthesis of amino acids—just like typically *holophytic* organisms. Euglena can live indefinitely without light, provided the surrounding medium contains adequate amounts of dissolved organic substances, especially carbohydrates. At the bottom of a pond, where there is an abundance of decomposing organic material, Euglena carries on a *saprophytic* nutrition. Some other green flagellates can also grow *holozoically,* utilizing the mouth and gullet for the *ingestion* of organic foods. But the mouth and gullet of Euglena have become vestigial, and are not capable of fulfilling these functions.

Parasitic Nutritions. A parasitic organism lives on or in another organism, deriving food from the living *host.* Parasitic species are found among all kinds of plants and animals,

although the parasitic habit tends to be more prevalent among lower organisms. Moreover, there is scarcely a single species of animal or plant which does not serve as host for one or more parasites. Some parasites, like lice, are *ectoparasites,* in that they never invade the interior of the host's body; but others, like the tape-worm, are endoparasites, which always penetrate into some internal cavity, or into the tissues or cells of the host.

The kind of nutrition practiced by a parasite depends largely upon its evolutionary background. Many parasitic animals, for

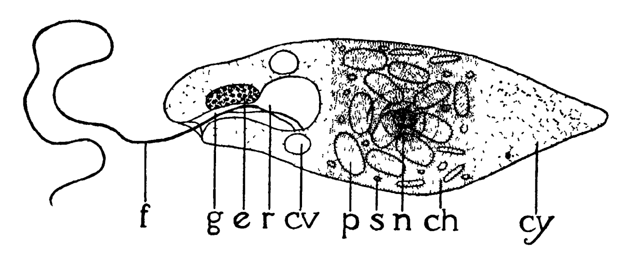
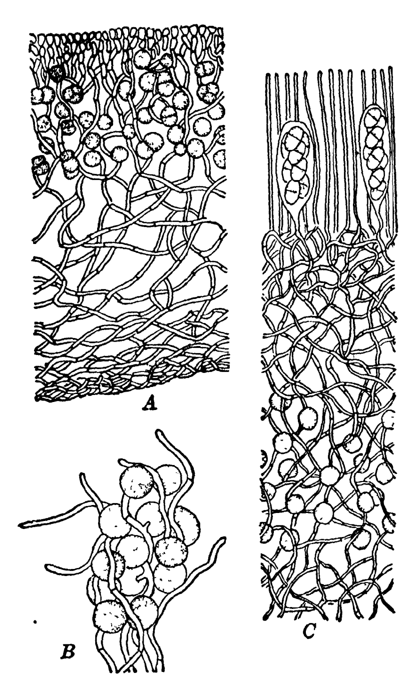


FIG. 70.—Euglena, a green flagellate. n, nucleus; cy, cytoplasm; ch, chloroplast; p, pyrenoid; s, starch grain; cv, contractile vacuole; r, reservoir; g, gullet; f, flagellum; e, red pigmented "eye spot."

example, are essentially holozoic, in the sense that they ingest the blood or tissues of their hosts. But parasitic plants get their nourishment essentially like saprophytes, absorbing organic substances directly from the body fluids, tissues or cells of their *living* hosts.

Many parasites do little or no harm to the hosts, aside from "stealing" a certain quantity of organic material. But many produce definite *diseases* in the hosts, either by direct injury to the cells and organs, or by producing toxic waste products. Among animal diseases, especially in man, many are caused by bacterial parasites (e.g., diphtheria, pneumonia, tuberculosis, gonorrhea, etc.); others are caused by parasitic protozoa (e.g., malaria, African sleeping sickness, syphilis, etc.); others by viruses (infantile paralysis, smallpox, mumps, etc.); and others by multicellular parasites (hook-worm, trichinosis, etc.). Among plant diseases, most are caused by parasitic fungi (rusts, smuts, molds, mildews, etc.), although a few are due to viruses.

Symbiosis. In certain cases not only the parasite but also the host derives benefit from their association. Such a mutually beneficial relation between parasite and host is called *symbiosis.* In this category, there are many interesting cases. The *lichens,* for example, are essentially dual organisms, for among the cells of these multicellular fungi there are always a number of unicellular green algae (Fig. 71). The alga donates its extra carbohydrate to the fungus, and the fungus aids the alga by contributing water and salts, absorbed in excess through the rhizoids. In this case the symbiotic organisms have become altogether dependent upon each other, and neither is able to live very long in the absence of the other.



From Smith, Overton, et al., *Text-book of General Botany.* By permission of The Macmillan Co.

FIG. 71.—The lichen is a dual organism. A, section of the mycellium showing the cells of a green alga nestled among the colorless hyphae of the fungus. B and C, reproductive stages.

Some fungi live symbiotically on and in the roots of higher plants (e.g., trees). These fungi aid the host plants in absorbing water and salts, through part of the mycelium which ramifies out among the soil particles; and in return, the root of the host provides the fungus with pre-formed carbohydrates. Many *herbivorous animals,* such as the cow, develop rich cultures of *cellulose bacteria* in the digestive tract. Here the bacteria convert considerable quantities of cellulose into glucose which is absorbed, in part by the host, and in part by the parasites. And in return the bacteria are afforded ideal conditions of warmth

and darkness while they absorb their other essential nutrients (water, salts, etc.) from the digesting food mass as it passes through the alimentary canal of the contented host.

Neutral Parasites. In some cases, a parasite does not harm or benefit the host in any tangible fashion. Such neutral parasites are, perhaps, even commoner than the harmful and beneficial types. For example, a number of species of bacteria inhabit the human digestive tract, especially in the region of the large intestine (p. 389). Aside from the fact that these bacteria appropriate small quantities of organic foodstuffs, no definite ill results from their presence in the gut. In fact, some of the intestinal bacteria of man are now known to benefit their host, by synthesizing several of the B-vitamins, of which some may be absorbed by the host.

A parasite may be neutral with reference to one kind of host, but definitely pathogenic to another. Such a case is provided by Cryptocotyle, a parasitic flatworm. The usual host of Cryptocotyle is a seagull, and adult gulls are quite immune to the presence of the parasite in their intestine. But mammals, such as the dog and fox, become seriously ill when they are infected.

Natural immunity depends to a large extent upon the capacity of the host's tissues to form antibody substances (p. 398). These *antibodies* counteract the toxic products of the parasite; and the development of natural immunity indicates that an association between the parasite and host has existed for a comparatively long evolutionary period.

Nitrogen-fixing Bacteria. One case of symbiosis deserves special emphasis, because it plays an important role in the conservation of *soil-fertility*. The *nitrogen-fixing bacteria* live symbiotically in the root tissues of several common species of higher plants (Fig. 72). These bacteria are the only organisms which are able to utilize free nitrogen (N_2) in their metabolism. Such a usage involves the conversion of free nitrogen (N_2) into the nitrate ($—NO_3$) form of nitrogen; and this *fixation of nitrogen* is an "uphill" process. Unlike most oxidation reactions, the fixation of nitrogen requires the *absorption* of considerable energy.

As a source for this energy, the N-fixing bacteria are dependent upon glucose (or other carbohydrate) donated by the root tissues of the host plant. And in return the host receives the excess

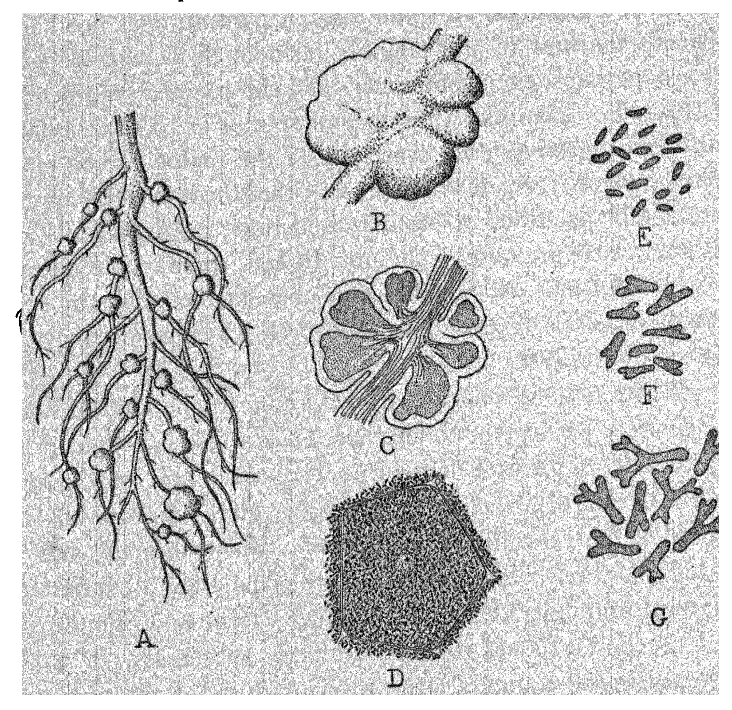


FIG. 72.—Symbiotic nitrogen-fixing bacteria. A, root of clover, with root nodules formed by symbiotic nitrogen-fixing bacteria (about natural size). B, a single nodule on root of lupin (somewhat magnified); C, section of same; D, a single cell of this nodule, filled with nitrogen-fixing bacteria. E, the nitrogen-fixing bacteria as they enter the root; F, G, later stages of these bacteria as they develop in the root nodules. (B, C, D, after Woronine; E, F, G, after Beijerinck.)

quantities of nitrate ($—NO_3$) compounds formed by the bacteria.

Rich cultures of the nitrogen-fixing bacteria live in the cytoplasm of the cells of nodule-like swellings which can be seen on the roots of the leguminous plants, such as beans and peas, and upon the roots of other plants, such as alfalfa and clover (Fig. 72). Frequently such crops are "rotated" with ordinary soil-depleting crops. The nitrate compounds formed by the

bacteria, with the help of the host plant, may be returned to the soil directly, if the crop is "plowed under"; or the nitrates may be converted into proteins which return nitrogen to the soil indirectly, via the metabolism of animals which have eaten the protein, or of saprophytes which accomplish their decay. In any event the nitrogen-fixing bacteria accomplish the important function of reclaiming free nitrogen and restoring it to "circulation" in other forms of life.

Chemotrophic Nutrition. The capacity of green plants to synthesize their organic essentials entirely from inorganic substances represents the primary source of organic foods utilized by other organisms. However, there are a few kinds of bacteria which also can grow in the complete absence of organic foods. These forms, lacking chlorophyl, cannot utilize solar energy to support their metabolism. Instead they resort to the *oxidation of certain inorganic substances*, thus obtaining energy for synthesizing glucose which then provides a source of matter and energy for the synthesis of the other organic components of their protoplasm. This kind of nutrition, in which *metabolism is supported by energy derived from inorganic oxidations*, is called *chemotrophic nutrition.* Inorganic substances capable of yielding energy through oxidation are not very abundant in the environment, and therefore chemotrophic modes of nutrition are restricted to a relatively small number of bacterial species.

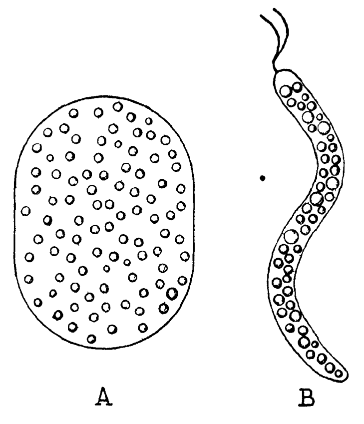


FIG. 73.—Sulphur bacteria; A, Achromatium (after Nadson and Wislouch); B, Thiospirillum (after Omeliansky). The spherical droplets are free sulphur.

The nutrition of the *sulfur bacteria* (Fig. 73) is typically chemotrophic. These bacteria oxidize hydrogen sulphide (H_2S), first into free sulfur (S) which is stored intracellularly (Fig. 73), and then into sulfate ($—SO_4$) compounds as further

energy may be needed. Other *chemotrophic bacteria* oxidize free hydrogen (to water); carbon monoxide (to carbon dioxide); iron salts (ferrous to ferric salts); etc. These inorganic oxidations provide the energy by which all these species *synthesize carbohydrate* from CO_2 and H_2O. And since they can also utilize inorganic nitrogen compounds for the synthesis of amino acids and proteins, the chemotrophic bacteria, *like the green plants*, are not directly dependent on other organisms for their essential nutrients. In fact, both chemotrophic and holophytic organisms are said to be *autotrophic*, or literally "self-nourishing."

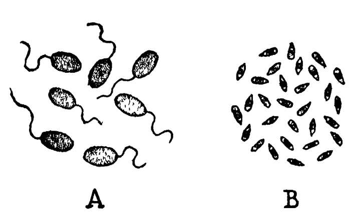


FIG. 74.—Nitrifying bacteria. A, Nitrosomonas, a nitrite-forming bacterium; B, Nitrobacter, a nitrate-forming bacterium. (After Winogradsky.)

The Nitrite and the Nitrate Bacteria. These autotrophic (chemotrophic) bacteria are especially important in relation to soil fertility. Much of the nitrogen from decomposing remnants of plants and animals in the soil is liberated by the saprophytic bacteria in the form of ammonia (NH_3), or of ammonium (NH_4—) salts, which cannot be utilized very readily by most green plants. But *nitrite bacteria* (Fig. 74, A) are present in all rich soil, and these organisms get energy for growth by oxidizing *ammonia* (or ammonium salts) into *nitrite* (—NO_2) salts. *Nitrate bacteria* (Fig. 74, B), possessing a somewhat different set of enzymes, also obtain energy by oxidizing the *nitrite* (—NO_2) salts into *nitrates* (—NO_3). Consequently the reclamation of nitrate nitrogen from its various organic combinations, depends upon the nitrite and nitrate bacteria, as well as upon saprophytic organisms. And in performing this function, the nitrite and nitrate bacteria gain energy with which to synthesize carbohydrates and the other organic components of their structure.

Various Modes of Nutrition: An Outline and Summary. According to their nutritional processes (Chaps. 7, 8 and 9), living organisms may be classified as follows:

I. *Autotrophic.* Can synthesize all essential organic components entirely from inorganic substances; therefore not directly dependent upon other organisms for foods.
   a. *Holophytic.* Utilize light (by photosynthesis) as a primary source of energy: *green plants.*
   b. *Chemotrophic.* Obtain energy by oxidizing inorganic substances: sulfur, nitrite and nitrate bacteria, etc.

II. *Heterotrophic.* Require at least a minimum of preformed organic compounds, and therefore dependent upon autotrophic organisms for food.
   a. *Holozoic.* Obtain organic foods by *ingestion, digestion,* etc.: *most animals.*
   b. *Saprophytic.* Absorb organic foods directly from the environment with or without external digestion: many *fungi,* including *most bacteria,* some *flagellates* and a very few higher plants.
   c. *Parasitic.* Obtain food from the bodies of other living organisms, in or on which they live: some species in almost every category of plants and animals.

III. *Mixotrophic.* Combine autotrophic and heterotrophic nutritions in various ways: many flagellates and a few higher plants (e.g., insectivorous species).

Holophytic and holozoic organisms have achieved great dominance, and practically all complex organisms are clearly divisible into two great groups: the plants and the animals. But among unicellular and simple colonial forms there are many border line organisms, and many radical departures from the main lines of evolution. In short, many methods of gaining matter and energy for growth and activity are found among simpler living bodies, but only the holophytic and holozoic modes of nutrition proved adequate for the sustenance of larger and more complex organisms.

Cyclic Usage of the Food Elements. Each organism, regardless of its mode of nutrition, grows at the expense of specific substances taken from the environment. Consequently the life

of a species cannot continue if any substance essential to its growth becomes exhausted. In the total economy of living things, however, the various food substances keep returning to the environment, ultimately in their original form and quantity. The earth is like a sealed but balanced aquarium. It receives no significant quantity of matter from other parts of the universe; but despite this material isolation, the earth can supply the material needs of all its inhabitants indefinitely—so long as light from the sun maintains its strength and continues to energize the metabolic cycles of existing living organisms.

The simplest way to realize the inexhaustibility of the *material* requirements of life is to trace the cycle of chemical changes by which each *element* returns to the environment after participating in the metabolism of various organisms. Each element participates in the formation of many protoplasmic compounds, but finally each returns to the environment in its original form. Thus the *carbon cycle*, or the *hydrogen cycle*, or the *nitrogen cycle*, describe the specific series of chemical changes by which each of these elements is utilized by different organisms and finally restored to the environment in the original form. Each element exhibits a different cycle, but only the *carbon* and *nitrogen* cycles will be described.

The Carbon Cycle. The environmental source of carbon for all organic syntheses is the carbon dioxide present in the atmosphere and natural waters of the earth (Fig. 75). The green plants (by photosynthesis) and to a much smaller extent the autotrophic bacteria (by chemosynthesis) take this carbon and build it into the molecular structure of carbohydrates; and these carbohydrates furnish all the energy, and a large part of the matter, needed by plants for the synthesis of proteins, lipins and other organic compounds in the protoplasm. The potential energy stored by green plants in various organic compounds is derived initially from the sun, and this energy becomes the driving force in the metabolism of virtually all other organisms. Organic compounds, created by plants and appropriated by animals, saprophytes and parasites, furnish energy and matter for the synthesis of all essential organic components in these hetero-

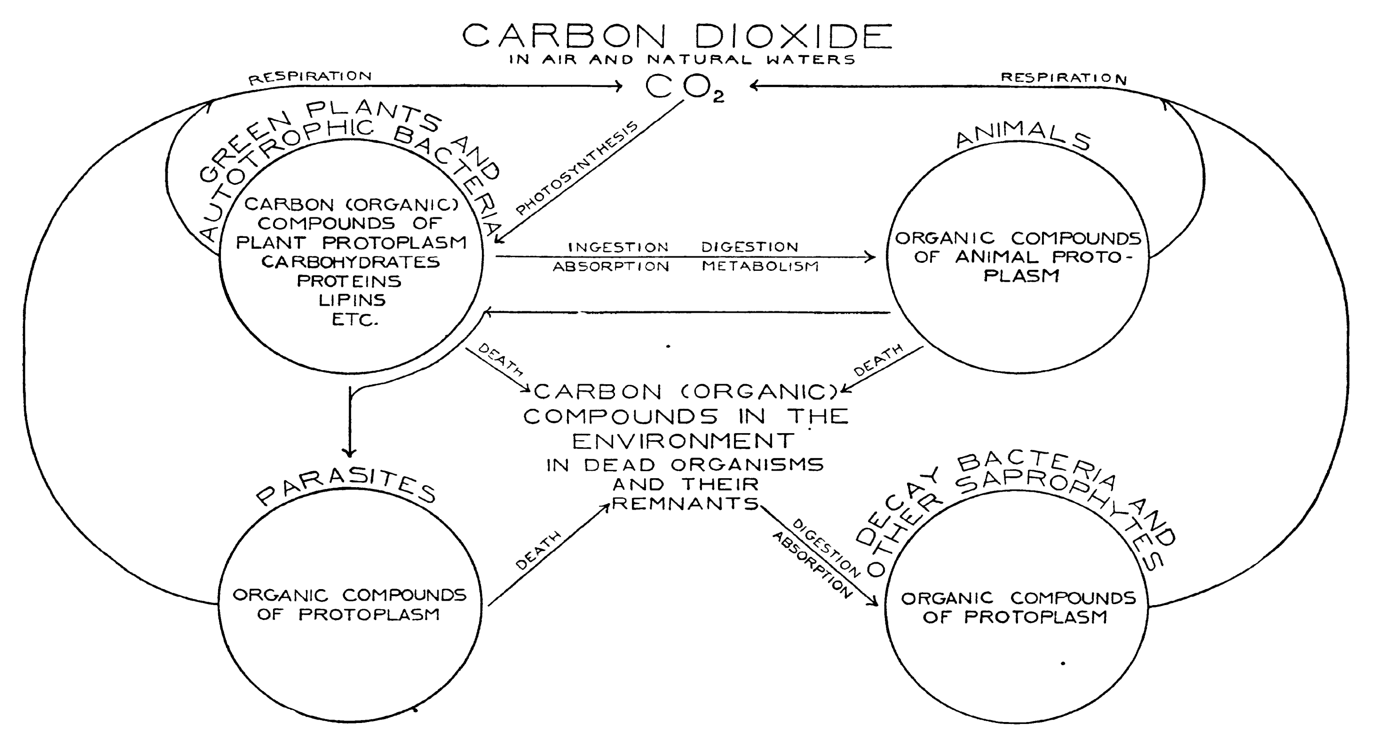


FIG. 75.—The cyclic usage of carbon compounds in various organisms. Compounds not included in the circles are free in the environment.

trophic organisms. Eventually, however, all organic compounds suffer decomposition; sooner or later all organic carbon returns to the environment as carbon dioxide, via the respiration of the organisms wherein the energy is utilized (Fig. 75).

The Nitrogen Cycle. The environmental source of nitrogen used by green plants for the synthesis of the amino acids and other essential nitrogen compounds, is nitrate ($—NO_3$) nitrogen, in the soil and natural waters of the earth (Fig. 76). The organic nitrogen compounds formed by plants are used later by animals and other heterotrophic organisms for the synthesis of their proteins. In living animals, proteins and other complex nitrogen compounds may be catabolized—in which case the nitrogen is excreted as urea and other simple nitrogenous wastes; or such protein may pass to the environment as a remnant of some animal. In any event, organic nitrogen in the environment is utilized by the putrefactive bacteria (Fig. 76), which excrete the nitrogen mainly in the form of ammonia (NH_3), but partially in the form of free nitrogen (N_2). Ammonia and ammonium compounds in the soil are utilized as a source of energy and matter, by the *nitrite bacteria,* which excrete nitrites; and the nitrites are used by the *nitrate bacteria,* which finally restore the nitrogen to the environment in its original nitrate form. The small quantity of nitrogen which tends to "escape from the cycle" as free nitrogen (N_2), is reclaimed by the *nitrogen-fixing bacteria.* In the roots of leguminous plants, these symbiont bacteria avail themselves of pre-formed carbohydrate for energy to oxidize free nitrogen to its nitrate form.

Solar Energy and the Perpetuation of Life. Each of the elements undergoes a *closed cycle* of chemical changes as it is utilized in the metabolism of various organisms. Consequently the material requirements of living things will not be exhausted so long as these cycles continue. To keep going, these cyclic changes do not require new matter, but they do require new energy; and this energy comes from the sun. Therefore the perpetuation of life as we know it, depends upon the light of the sun.

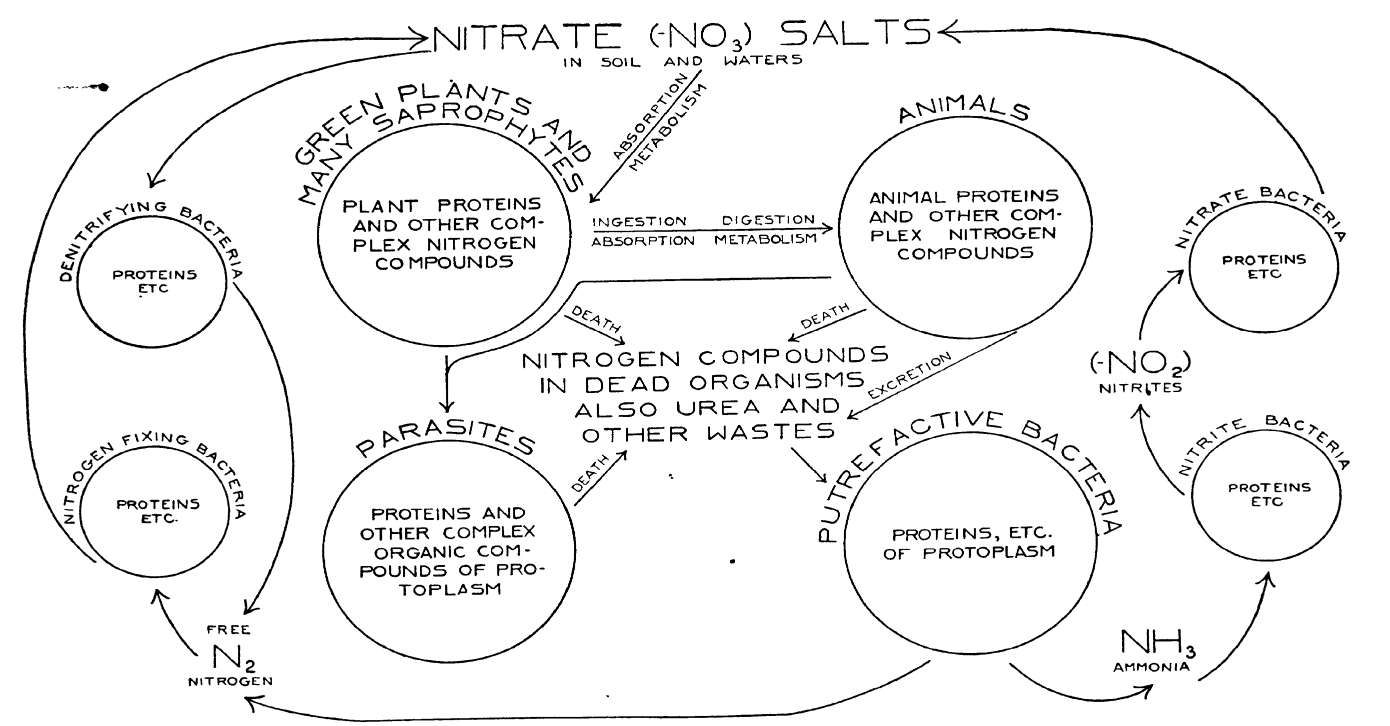


FIG. 76.—The cyclic usage of nitrogen compounds in various organisms. Compounds not included in the circles are free in the environment.

The radiant energy absorbed by the chlorophyl of green plants is transformed into the potential energy of free oxygen and glucose—and indirectly into the potential energy of other organic compounds. All organisms get their energy from organic substances, and in the process eventually convert them back into their original form. The energy liberated by the complete oxidation of a given amount of carbohydrate is exactly equal to that previously absorbed in the photosynthesis of this carbohydrate. All energy transformations, whether in animate or inanimate bodies, obey the first *Law of Energy*. Energy is conserved in that the total quantity of energy remains the same regardless of all transformations. But the energy released by the oxidation of carbohydrate does not appear in its original form. Much is liberated directly as *heat*, and only part is transformed into the chemical potential energy of other complex organic compounds, such as proteins, lipins, etc. Eventually all the organic compounds in protoplasm are decomposed. In the catabolism of various cells, these decompositions give forth many kinds of energy, *mechanical*, *electrical*, *osmotic*, etc.—but eventually all energy liberated in organisms is transformed into *heat*. Therefore the net result of all activities in all living organisms is the transformation of a certain quantity of energy from *light* finally into *heat*.

The sun is the source of practically all the available light energy on our earth. The sun liberates stupendous quantities of energy, probably by atomic disintegrations which occur spontaneously at very high temperatures; but only a small fraction of the kinetic energy from the sun falls upon our earth. Of this small fraction the greater part strikes inanimate bodies (rocks, water, soil, etc.), which absorb the light and transform it *immediately* into heat. Only that minute fraction of solar energy which happens to fall upon the green plants escapes immediate degradation. But this fraction launches upon a peculiar and roundabout series of transformations which motivate the complex activities of living organisms. Then finally this energy likewise becomes converted entirely into heat.

Unlike matter, the energy utilized by living things does not form a closed cycle. This energy continuously runs "downhill" —from light to heat—turning the wheels of life as it flows. As it is formed, the heat is dissipated; it warms the water, the soil, the air, etc., and gradually it escapes into interstellar space. What eventually may become of this dissipated energy—whether it may be transformed back into some useful form in some unknown part of the universe—we do not know. So far as our earth is concerned, all processes, in living and in non-living nature, conform with the Second Law of Energy: all forms of energy are continually degraded into heat and dissipated. Therefore the extinction of life as we know it must inevitably occur—if and when the radiant energy of the sun becomes too feeble to support the metabolism of the green plants and, indirectly, of other organisms.

TEST QUESTIONS

1. Define the term *fungi*. Name eight kinds of fungi.
2. Identify and exemplify each of the following terms: (a) mycelium; (b) hypha; (c) rhizoids; (d) sporangiophore.
3. Name at least three kinds of saprophytic organisms. What is distinctive about this mode of nutrition?
4. Discuss anaerobic metabolism in yeast. What is the significance of this type of metabolism
   a. to the yeast?
   b. to mankind?
5. How are the yeast and the bread mold different, as regards their capacity to utilize: (a) starch; and (b) nitrate salts, present in the culture medium?
6. Differentiate between *decay* and *putrefaction*. What mode of nutrition is exemplified by the organisms that are involved in these processes?
7. Name three kinds of bacteria which are important in the decomposition of carbohydrates and fats, specifying the product or products formed by each.
8. Specify the final end-products of decay and putrefaction (taking these processes as a whole).
9. Explain the general importance of decay and putrefaction in

relation to: (a) the kinds of matter which are disposed of; and (b) the kinds of matter which are liberated.

10. What is a parasite? Differentiate between harmful and neutral parasitism, citing two examples in each case.
11. Explain the nature of symbiosis, citing at least three specific examples.
12. Explain the phrase *cyclic usage of the food elements*, using the *carbon* cycle to exemplify the discussion.
13. Name five different kinds of bacteria which play a significant role in the nitrogen cycle, and in each case specify: (a) the habitat of the species; (b) its mode of nutrition; and (c) the nitrogen compounds used and produced by the species (use equations, if possible).
14. Classify various organisms on the basis of their nutrition, naming at least one specific organism in every group.
15. Explain the relation of light energy to the other forms of energy expended by living organisms. How is this problem related to the eventual extinction of life upon this planet?

FURTHER READINGS

1. *Principles of Soil Microbiology*, 2nd Edition, by Selman A. Waksman; Baltimore, 1932.
2. *The Fitness of the Environment*, by L. J. Henderson; New York, 1913.
3. *Fundamentals of Bacteriology*, by Martin Frobisher, Jr.; Philadelphia, 1944.

CHAPTER 10

RESPONSIVENESS IN SINGLE CELLS

THE CHANGING conditions within and around each living body constantly act as stimuli, which excite the organism to perform a variety of responses. The dog searches for food when stimulated by the hunger contractions of his empty stomach; or he may lie down in a shady spot, if overheated by the sun. *Responsiveness* includes the sum total of all of an organism's reactions to stimuli; and our present aim is to analyze the many factors which determine the responses of relatively simple organisms.

Discontinuous (Abrupt) vs. Continuous (Slow) Responses. The most characteristic responses of organisms are of very short duration. They flare up and quickly subside after the stimulation ceases—as when one shies from a stone or sneezes from some dust. The magnitude of such *discontinuous responses* is out of all proportion to the strength of the stimulation. Some very slight stimulus—of sight, touch, sound, or what not—precipitates a very energetic reaction.

In abrupt or discontinuous responses the stimulus does not provide the energy expended during the reaction. Like the pressure on the trigger of a rifle, the stimulus merely precipitates the liberation of a sudden burst of energy, and this burst subsides as soon as the responsive act has been performed. Accordingly discontinuous responses are also called "explosive responses," and the stimulus is said to display a "trigger action."

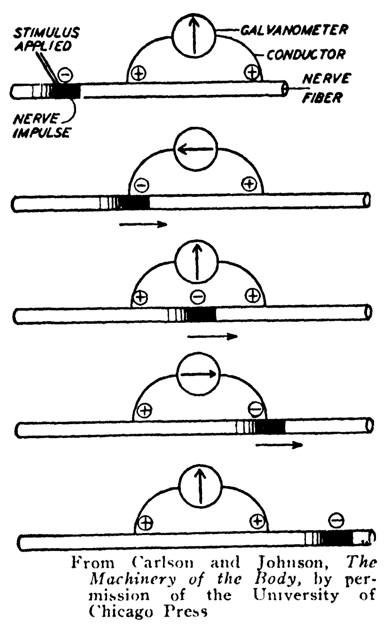
In other cases, however, a very gradual and enduring change of condition (such as light, temperature, atmospheric pressure, etc.) leads to an equally gradual and enduring change in the

general form and activity of the organism. A continuous exposure to the sun, for example, produces a gradual browning of the skin; or a lengthy sojourn at high altitude leads to a gradual enrichment of the hemoglobin of the blood. In such *continuous responses,* the quantity and quality of the bodily changes depend in large measure upon the quantity and quality of the stimulating factors. In the broadest sense such gradual changes in the organism may be called responses, and the environmental factors may be referred to as stimuli. But for the present, the discussion will include only responses of the discontinuous or "explosive" type, in which the stimulus exerts a "trigger-like" action.

Successful Stimulation: The State of Excitation. *Excitability* is a universal protoplasmic characteristic. When successfully stimulated every cell displays a wave-like change of structure and activity which originates at the point of stimulation, spreads throughout all parts of the protoplasm, and then subsides. This abrupt and strictly temporary disturbance of the ordinary resting condition of the protoplasm is designated as *excitation.* The *excited state* is invariably the forerunner of any definite cellular response—such as the contracting of a muscle or the secreting of a gland.

Some stimulated cells, like muscle cells, perform some visible action each time they are stimulated, and in such cases the visible action serves to indicate that a stimulation has been successful. But for cells, like nerve cells, which are incapable of executing any visible act, several other criteria of successful excitation are available. Invariably a small electric current—the *action current* —is discharged at the excited part of a cell, and this current spreads throughout the protoplasm in exact synchrony with the spread of the excitation. Excitation is also accompanied by the *liberation* of a small quantity of *heat,* and in most cases at least, excited cells display a temporary *increase* of permeability. Apparently excitation precipitates a temporary flare-up in the metabolism of the cell; and during excitation special enzymes and substrates, which are not used during periods of rest, are utilized by the excited cell.

The Action Current. The *action current* is an infallible sign of successful excitation. It has been measured accurately in many kinds of animal and plant tissues and in quite a number of individual cells. In the case of a single cell, difficulty is encountered unless the cell, like a nerve or muscle cell, is long enough to allow for the placement of electrodes leading to a *galvanometer* (Fig. 77).



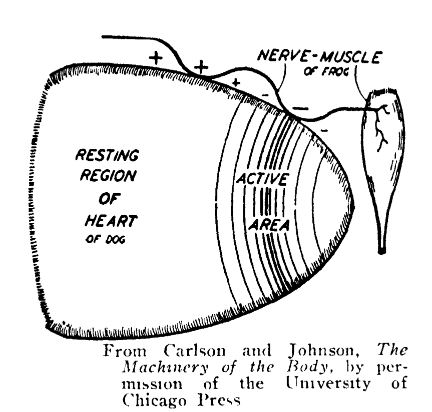
From Carlson and Johnson, *The Machinery of the Body*, by permission of the University of Chicago Press

FIG. 77.—Electrical changes in active nerve. A nerve impulse traveling along a nerve fiber betrays its presence by its negativity, as compared with the positivity of resting, inactive regions of the nerve fiber.

The strength of the action current varies between 0.01 and 0.1 volt, although in animal cells it tends to approximate the higher value. The current generated in one cell, or group of cells, may be strong enough to spread to neighboring cells, thus relaying the excitation (Fig. 78). In the human heart, for example, the excitation for each beat originates in a small mass of tissue in the wall of the right auricle. From this point the action current travels along a highly specialized group of muscle fibers, reaching the other auricle and the ventricles in time to touch off their contractions just at the proper instant. In taking the *electrocardiogram,* the physician records the strength and pattern of the action current as it spreads throughout the heart, and these measurements prove helpful in diagnosing cardiac function.

Other Phases of Excitation. Momentarily the plasma membrane of an excited cell becomes more permeable, especially to ionized substances; and this increase of permeability has an important bearing upon the propagation of the action current. At rest the plasma membrane is polarized in such a

way that positively charged ions are arrayed very regularly at the external surface, opposite to and insulated from a deeper-lying layer of negative ions (Fig. 79). Apparently each excitation involves a temporary break-down of the insulating properties of the membrane, so that locally and momentarily the ions come together, and the membrane loses its charge. In any event, an excited part of the cell always becomes negative relative to the unexcited parts. Moreover, this difference of potential sets up a series of local action currents, which originate at the point of stimulation (Fig. 79).



From Carlson and Johnson, *The Machinery of the Body*, by permission of the University of Chicago Press

Fig. 78.—Electrical changes in contracting heart muscle. Each time the heart beats, the frog muscle contracts because the frog nerve is stimulated by the electrical currents developed by the contracting heart muscle.

Apparently the polarized condition is an essential factor in maintaining reactivity in living cells. Whenever the polarization is locally abolished, excitation occurs; and conversely, whenever excitation occurs, the polarization is momentarily abolished. These changes are not necessarily confined to the plasma membrane. They may extend via internal interfaces throughout all the protoplasm of an excited cell.

The changes of the protoplasmic structure which accompany excitation change the metabolism of the cell. Immediately the excited cell begins to liberate extra heat, but it does *not* consume extra oxygen. In fact, many cells, like nerve and muscle, can continue to respond to stimulation for quite a while after their oxygen has been used up. This *excitation metabolism* should not be confused with the *recovery metabolism*, which *follows* excitation. Recovery always involves an extra consumption of oxygen and an extra production of carbon dioxide. In short, the recovery reactions supply energy for restoring the

protoplasmic structure to its original excitable state. Consequently when recovery metabolism is inhibited, as by lack of oxygen, the cells very quickly become fatigued. Then no further

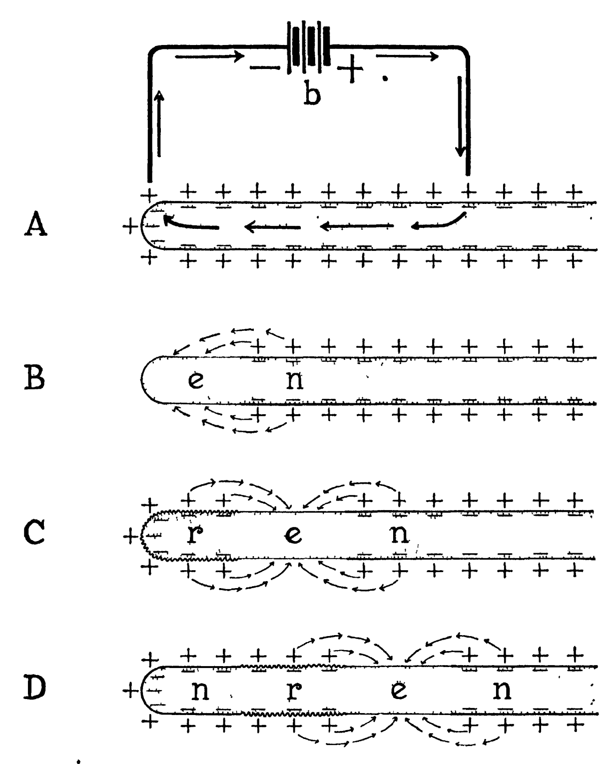


FIG. 79.—Diagrams illustrating the theory of transmission of excitation. A, a resting (unexcited) nerve fiber; its surface membrane is electrically polarized, as indicated by the signs; an artificial electric current is passed through the nerve, in the direction shown. B, the nerve fiber becomes excited at the point of application of the negative electrode, where its normal polarization is abolished. C, E, transmission of the state of excitation along the fiber. b, battery; n, normal (unexcited) region of the nerve fiber; e, excited region; r, refractory region. Heavy arrows indicate direction of the stimulating current, light arrows direction of the action current.

responses can be obtained until the tissue has been allowed to rest in the presence of an adequate supply of oxygen.

The Refractory Period. Immediately following excitation, before the protoplasm has returned to its resting state, there is a brief *refractory period*, during which the cell cannot be re-

excited by any stimulus, however strong. The duration of this refractory period differs in different cells, from less than 0.001 second (in nerve cells) to a number of seconds (in plant cells). Due to the refractory period, the state of excitation is self-limiting: a cell cannot remain continuously in the excited state. The refractory period has an important bearing on the rhythmicity of certain responses, such as the beating of heart muscle, or of cilia, since the refractory period imposes a definite limit upon the frequency at which the responses are able to recur. Many responses which appear to endure for some time, like the prolonged contraction of a body muscle, actually represent a series of rapidly recurring responses. In the case of the muscle this can be seen in the electrical records, for the electromyogram always shows a series of action currents occurring synchronously with the excitations.

Stimuli and Stimulation. Any physical or chemical *change* occurring within or around a living body may act as a stimulus, provided the quantity, quality and rate of the change are properly adjusted to the sensitivities of the cell or cells which are to be excited. The various kinds of stimuli capable of exciting cells and organisms generally may be classified as follows:

Mechanical stimuli: Contact, pressure, sound.
Thermal stimuli: Changes of temperature.
Osmotic stimuli: Changes in the concentration of substances.
Chemical stimuli: Changes in the kinds of substances present in or around the organism.
Electrical stimuli: Changes in strength or direction of electric currents.
Photic stimuli: Changes in the intensity, color, or direction of light.

Most cells *can* be excited by several kinds of stimuli, but usually each kind of cell is especially susceptible to a particular kind of stimulation. Successful stimulation of the retinal cells of the eye, for example, requires an unbelievably small quantity of light, whereas another kind of stimulus, such as a blow on the temple, can arouse sensations of light ("seeing stars") only if the intensity of the stimulus is relatively great. In the case of

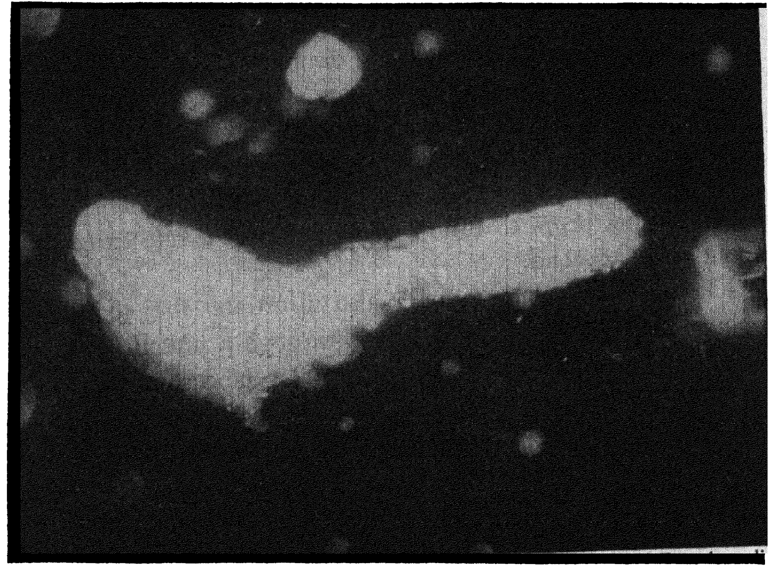
specialized cells, non-specific stimuli are relatively ineffective; but there is one important exception to this general rule. All cells are easily excited by electrical stimulation, and this fact emphasizes the role of the action current as a normal agency in propagating the excitation, once a cell has been aroused.

The *rate* of the stimulating change has a distinct influence upon its effectiveness, as can be demonstrated with light as an example. The rapid brightening or dimming of a light is always noticeable. But if the change develops slowly, it may fail to excite the cells of the retina, and consequently it is not perceived. Too rapid a change may also fail to excite the retina. An intermittently flashing light is perceived to be continuous if the individual flashes begin to follow one another at a rate exceeding about 14 per second.

Electrical stimulations will also illustrate the foregoing points. If a direct current is passed through a muscle, no contraction occurs except at the moment when the current is turned on or off, i.e., while a *change* of current intensity is taking place. But the *rate* of the change must also be adjusted properly, if the muscle is to be excited. Even with adequate voltage, no excitation occurs if the current rises or falls too slowly or too quickly.

Receptors, Conductors and Effectors. In multicellular organisms a typical response involves not one, but a series of cells, each playing a specialized role. Let us take, for example, the closing of the pupil, which occurs when light is shone directly into the eye. In this response the light does not act directly upon the muscle cells of the iris, which control the size of the pupil opening. Only the cone *cells* of the retina, deep inside the eyeball, are directly excited by the light. Thus the cone cells act as *receptors* when light is the stimulating agency. But after the cone cells receive the stimulus, they relay the excitation to a series of *nerve cells*, which serve as the *conductors* of the responsive system. The nerve cells conduct at high speed, and within about 0.01 second they transmit the excitation to the muscle cells of the iris. Thus the muscles are the *effectors* of this response, in that the muscles contract and close the pupil.

A *receptor* is any part of the organism that displays a special sensitivity to excitation, usually by a specific kind of stimulus. The main function of the receptor is to generate excitations and relay them to the conductor structures. A *conductor* is any specialized part of the organism which serves to propagate excita-



From sound film, *The Nervous System;* courtesy of Encyclopaedia Britannica Films, Inc.

FIG. 80.—Response of an Amoeba after being touched by a glass rod (right). The specimen moves away in a co-ordinated manner, indicating that the excitation is *conducted* from the site of stimulation to all parts of the cell.

tions toward an effector. And finally, an *effector* is a specialized part of the organism which executes the final or "active" phase of a response.

In the higher animals, including man, the receptors are mainly represented by the sensory cells and the sense organs; the conductors, by the cells of the nervous system; and the effectors, by the muscles and glands. But in many unicellular organisms there are receptor, conductor and effector structures, differentiated within the single cell.

Responsive Mechanisms in One-celled Organisms. When the advancing pseudopodium of an Amoeba is probed with

a micro-instrument, the Amoeba withdraws the pseudopodium and starts moving in another direction (Fig. 80). Plainly the excitation does not remain localized at the point where the stimulus is *received*. It is *conducted* throughout the cell, otherwise the several pseudopodia, which serve as *effectors*, could not act in a concerted fashion, as the Amoeba alters the direction of its locomotion. In the Amoeba, apparently, any part of the cell may serve as receptor, conductor, and effector, and scarcely any definite differentiation of these parts can be recognized.

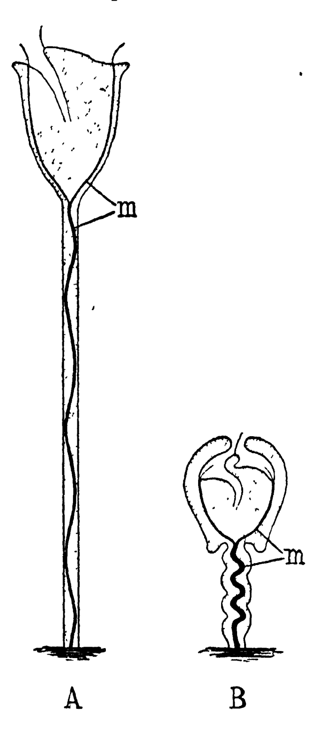


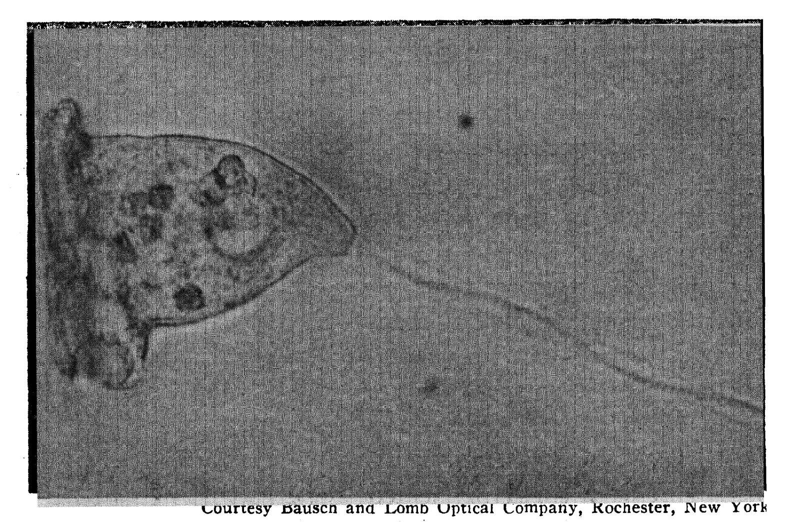
Fig. 81.—Vorticella, a stalked ciliate protozoan; A, expanded; B, contracted. The contraction is effected by the shortening of the myonemes, m. (The other intracellular structures—nucleus, vacuoles, etc.—are omitted from the figure.)

Perhaps the commonest *specialized receptors* in unicellular organisms are the red-colored *chromatophores*, or "eye-spots," which are found in many green flagellates (Figs. 63 and 70). Each chromatophore is a small pigmented granule, which is generally regarded as a *photoreceptor*. Probably many of the light-seeking responses which are characteristic of the phytoflagellates are initiated in these receptor structures.

The *cilia* and *flagella* of the Protozoa and free-swimming algae serve as effectors of mechanical response, and probably also as receptors of tactile stimuli, since frequently these parts are first to make contact with external objects. Many Protozoa, especially ciliates, also possess internally placed contractile fibrils, called *myonemes* (Figs. 81 and 82). These intracellular effectors act more or less like the muscle fibers of higher animals. By shortening quickly and forcibly, the myonemes enable a one-

celled organism to change its shape, sometimes in very drastic fashion.

Specialized conductors are relatively rare among unicellular organisms. The undifferentiated protoplasm of these cells propagates an excitation at a comparatively slow rate (see p. 575); but within the single cell this is fast enough. Certain large ciliated Protozoa, however, display a delicate network of intra-



Courtesy Bausch and Lomb Optical Company, Rochester, New York

FIG. 82. A living Vorticella, expanded condition.

cellular threads, called *neurofibrils*. The neurofibrillar network forms an inter-connection between the cilia all over the body, and it is thought that the neurofibrils are a conductor system, which co-ordinates ciliary activity.

Ciliary Movement. Broadly speaking the term *ciliary movement* includes the beating of flagella as well as of cilia, although cilia differ from flagella in being shorter, stouter and more numerous. Flagella are characteristic of many bacteria, Protozoa and algae, and of the sperm cells of higher plants and animals generally. Cilia are found in a large group of the Protozoa (p. 741) and in the ciliated epithelia of the respiratory and genital tracts of higher animals.

In action, a cilium swings stiffly and rapidly in one direction,

then limply and slowly returns to its original position (Fig. 83). In most ciliated epithelia the stiff *effective stroke* is always in one direction. For example, in man's bronchial passages, the ciliary beat is always upward, so that dust and other foreign particles are carried from the lungs up through the trachea into the throat. In the Protozoa, however, the direction of the ciliary beat may be reversed temporarily, as when a Paramecium backs away from an obstacle.

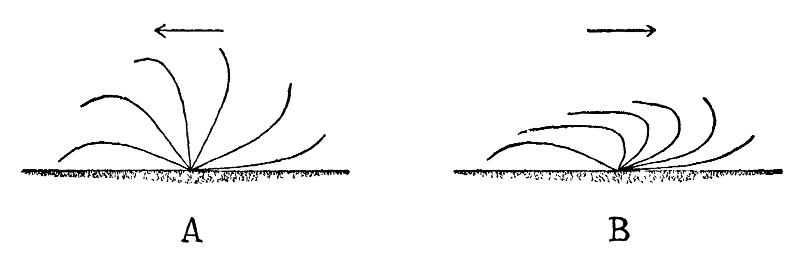


FIG. 83.—Diagram illustrating movement of a cilium; A, effective stroke; B, recovery stroke. (After Gray.)

An active flagellum displays a whirling movement, especially at the free end, like the twirling of a whip. In some cases this action pulls the cell forward, like the propeller pulls an airplane; but in others, it pushes the cell, like the screw pushes a steamship.

The *axial core* of a cilium is composed of a solidified strand of protoplasm, called the *axial filament.* This axial core is comparable to the *myofibrillae* of muscle cells (p. 556), and probably contracts with each effective stroke of the cilium.

Amoeboid Movement. The Amoeba moves by means of *pseudopodia,* which are *strictly temporary* protoplasmic extensions, projected from the surface of the cell. During locomotion, the protoplasm of Amoeba continues to flow forth into the leading pseudopodium, so that the cell moves as the pseudopodium extends. Also the pseudopodia play a part in ingestion, when the Amoeba engulfs small food particles from the surrounding medium.

Amoeboid movement is not restricted to Amoeba and other Protozoa, but is also encountered in the white blood cells (leu-

cocytes) and connective tissue cells (fibroblasts) of higher animals. Leucocytes migrate throughout the body by amoeboid movement, squeezing their way among the cells of other tissues, and engulfing particles of organic debris and bacteria, if the tissue is infected. This activity of leucocytes is called *phagocytosis,* although essentially phagocytosis resembles the process of ingestion in Amoeba and other free-living cells. In the human

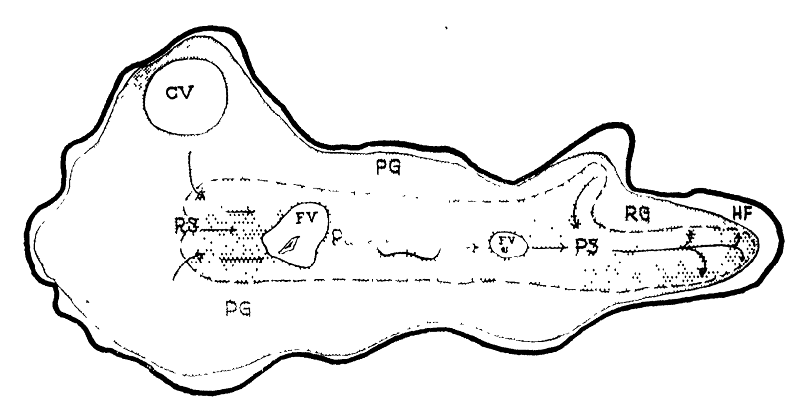


FIG. 84.—Amoeboid movement involves both gelation and solation (see text). PG, plasmagel; PS, plasmasol; RS, region of solation; RG, region of gelation; CV, contractile vacuole; FV, food vacuole; N, nucleus; HF, hyaline fluid (ectoplasm).

body there are also certain epithelial cells, located especially in the liver and spleen, which act as *stationary phagocytes.* Despite the fact that these cells are anchored in a fixed position in an epithelial surface, each is able to thrust forth pseudopodia from its free end and to engulf solid particles from the blood stream, upon which the epithelium borders.

By watching a pseudopodium as it extends from the surface of an Amoeba, one can gain some concept of how the movement is effected. Not all the protoplasm flows as the pseudopodium extends. In fact there is a semisolid layer of protoplasm—the *plasmagel*—which completely encases the fluid (flowing) protoplasm, or *plasmasol* (Fig. 84). Many experiments indicate that gelated protoplasm possesses a capacity to contract, and the plasmagel of the Amoeba probably contracts, exerting a pres-

sure upon the plasmasol and causing it to flow forward. At the tip of an advancing pseudopodium the plasmagel is virtually absent, so that the forward flow is impeded mainly by the elastic surface membrane. Moreover, the sol, upon reaching the tip of a pseudopodium, is diverted toward the side walls, where gelation occurs. Thus the plasmagel of the side walls is built up as a pseudopodium extends. Simultaneously, near the posterior extremity of the Amoeba, the plasmagel is solating, forming new plasmasol which adds itself to the forward-flowing stream. There are, however, a number of unknown factors as to the mechanism of amoeboid movement. Virtually nothing is known about the metabolic reactions which determine the solling and gelling of the protoplasm, nor about how these processes are co-ordinated in the different parts of the cell.

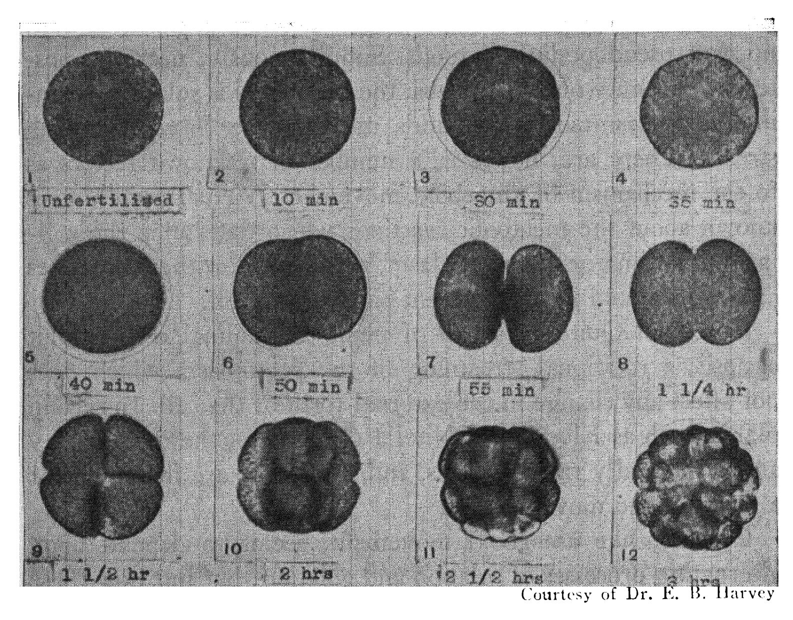
Cyclosis. Quite a variety of plant and animal cells exhibit cyclosis, a rotational streaming of the protoplasm which does not effect any change in the external form of the cell. In certain plants, such as Elodea and Nitella (Fig. 127), the cells display an exceptionally rapid cyclosis, and these cells are favorable for a study of the movement.

Cyclosis, like amoeboid movement, seems to depend upon alternating processes of solation and gelation; but just how these reactions produce streaming is hard to understand. In Nitella, the streaming can be stopped and started by a variety of stimuli; and each successful stimulation produces a typical wave of excitation, attended by a slow action current. Cyclosis serves to accelerate the distribution of substances from one part of the cell to another, or from one cell to neighboring cells—in multicellular organisms. In many cells, cyclosis goes on more or less continuously, even in the absence of any apparent external stimulation. However, such a continuous cyclosis probably depends upon a series of internal stimuli, which arise from rhythmically recurring processes in the metabolism of the cell.

Cleavage. Cleavage is the pinching movement by which an animal cell cuts itself into daughter cells; and this movement has been studied most extensively in dividing eggs (Fig. 85). These large cells are very favorable because they cleave on a

regular schedule, following the time when the sperm make contact with the eggs.

When a sperm comes into contact with an egg, a definite excitation arises at the contact point, and this excitation sweeps over the entire egg surface, visibly changing the protoplasmic



Courtesy of Dr. E. B. Harvey

FIG. 85.—Early development of the Arbacia egg. Note: the fertilization membrane (2-12); the first cleavage furrow (6-7); the four-cell stage (9); the eight-cell stage (10); and two many celled stages (11 and 12).

structure. The original stimulus precipitates a long series of responses which include: the lifting of the fertilization membrane (p. 322), the penetration of the sperm head, the approach and fusion of the gamete nuclei, the divisions of the zygote nucleus, and the successive *cleavages* of the one cell into many (Fig. 85).

The cleavage *furrow* (Fig. 85), which cuts through the cell, first appears as a shallow groove encircling the egg. Then gradually the furrow deepens, and in a few minutes, it passes through the center of the egg and completes the division of the cytoplasm.

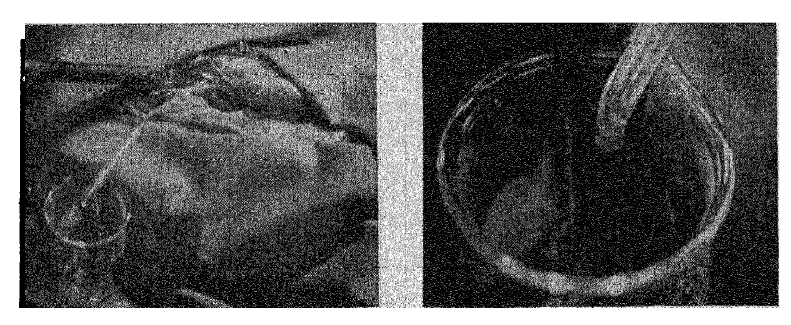
Recent evidence provides several clues as to the nature of the force which enables the furrow to cleave the cell. Several minutes before the furrowing starts, a surface layer of protoplasm, where the furrow is about to form, suddenly becomes solidified into a very firm gel. This girdle of gelated protoplasm is only about 5 microns thick, but it appears to contract forcibly, pinching the egg in two. If the cleavage girdle is prevented from gelating—by mechanically agitating the protoplasm with a microneedle, or by a variety of other means—the furrow does not form. Or if a liquefication of the protoplasm of the cleavage girdle is induced after the furrowing has started, the furrow gradually recedes.

Secretion. Strictly osmotic exchanges between the cell and its environment occur on a spontaneous basis, and do not require any expenditure of energy. But in some cases the cell *expends energy* in forcing substances to pass across its living membranes, and such responses are called *secretions.*

In *multicellular* organisms, the effectors of secretion are *glands.* Excitation of a salivary gland, for example, can be detected whenever its motor nerve is stimulated (Fig. 86). Action currents from the secretory cells are discharged so long as the motor nerve is stimulated, and saliva continues to flow from the gland during the period of excitation.

Among *unicellular* organisms, the most familiar secretional effectors are the gastric and contractile vacuoles. Food in the gastric vacuole of an Amoeba, for example, excites the cell to secrete digestive enzymes across the vacuole membrane, from the surrounding cytoplasm. This mobilization requires the cell to do work, since enzyme molecules are too large to penetrate the membrane spontaneously. In some way the cell manages to pass the enzymes into the digestive vacuoles, but exactly how this is done is problematical. In stained specimens the enzyme material appears to accumulate on the outer surface of the vacuolar membrane in the form of visible granules; and these granules seem to erupt through the membrane into the vacuole proper.

How the contractile vacuole functions is likewise not well understood. The content of the vacuole is mainly water and is distinctly hypotonic to the protoplasm. As a vacuole swells, therefore, water is forced to flow "uphill" from a region of lesser to a region of greater concentration. Accordingly the cell must expend energy in forcing water to flow into the vacuole, and this energy must be derived ultimately from metabolism.



From sound film, *The Digestion of Foods;* courtesy o Encyclopaedia Britannica Films, Inc

A B

FIG. 86.—A, stimulation of the motor nerve to the pancreas is followed shortly by B, a flowing of the pancreatic juice.

Thus the contractile vacuole stops functioning when a cell is deprived of oxygen, or when its metabolism is depressed by narcotics; and gradually the cell swells until it reaches the bursting point.

Responses of Multicellular Organisms. It should be emphasized that the complicated behavior of higher organisms depends upon responses occurring in the individual cells. Receptivity, conductivity, and the capacity to execute effective responses are general attributes of all cells. However, considerable specialization has occurred among the cells of higher organisms, so that well-differentiated tissues and organs serve as the receptors, conductors, and effectors in the highly integrated responses of all higher forms.

TEST QUESTIONS

1. Define the term *stimulus*. Differentiate between internal and external stimuli, citing an example of each.
2. Differentiate between continuous and discontinuous responses, citing two examples in each case.
3. Specify four criteria which distinguish the *state of excitation*, i.e., four differences between an *excited* and an *unexcited cell.*
4. Discuss the *action current* in relation to: (a) plant cells; (b) animal cells; (c) heart muscle; (d) the polarity of the plasma membrane.
5. Classify the various kinds of stimuli.
6. Both the rate and the magnitude of a stimulating change are important in determining the effectiveness of a stimulus. Explain this statement in terms of the human retina.
7. Differentiate between receptors, conductors and effectors using: (a) various unicellular organisms; and (b) man, to exemplify the discussion.
8. Differentiate between: (a) cilia and flagella; (b) the effective and the recovery strokes; (c) an axial filaments and a myofibrillae; (d) the plasmagel and the plasmasol; (e) amoeboid movement and cyclosis.
9. Both amoeboid movement and cleavage probably depend upon the capacity of protoplasm to undergo gelation. Explain and discuss this statement.
10. Secretion is an energy expending process. Explain and discuss this statement.
11. Receptivity, conductivity and the capacity to execute definite responses are general attributes of living cells. Explain and discuss this statement.

FURTHER READINGS

1. *Unresting Cells*, by Ralph W. Gerard; New York, 1940.
2. *The Conduction of the Nervous Impulse*, by Keith Lucas; New York, 1917.
3. *Injury, Recovery and Death, in Relation to Conductivity and Permeability*, W. J. Osterhout; Philadelphia, 1922.

PART II

MULTICELLULAR PLANTS

CHAPTER II

REPRODUCTION IN MULTICELLULAR PLANTS

Alternation of Generations. Higher plants reproduce in two ways: (1) *sexually*, by forming gametes; and (2) *asexually*, by forming spores. The sexual stage of the plant alternates regularly with the asexual stage; and usually the sexual generation differs so widely from the asexual generation that it is difficult to recognize the two generations as stages in the life cycle of the same species. But the sexual plant always produces eggs which develop (when fertilized) into an asexual plant; and the asexual plant always produces spores which give rise again to the original sexual plant. Accordingly the sexual generation, which produces gametes, is called the *gametophyte;* and the asexual generation, which produces spores, is called the *sporophyte*. Moreover, the cells of the gametophyte are always *haploid*, while the cells of the sporophyte are always *diploid*.

Life Cycle of a Fern. An alternation of generations is the common evolutionary heritage of all higher plants, although the character of the life cycle differs in detail in the different plant groups. First to be described will be the life cycle of a

fern. All ferns (about 4,000 species) display a similar cycle; and in a broad sense, the fern life cycle will serve as the prototype for higher plants generally.

The Sporophyte. The large familiar fern plant (Fig. 87) represents the sporophyte generation, i.e., the *diploid asexual* form of the fern. The green parts of the fern, which are seen above the ground-level, consist entirely of the *leaves*, or *fronds*. Each complexly subdivided leaf arises from a horizontal *underground stem* (Fig. 87); and numerous fine *roots* grow downward from the stem into the soil. The sporophyte carries on an independent holophytic nutrition. It may live for a number of years, producing one crop of spores annually.



From Fuller, *The Plant World*

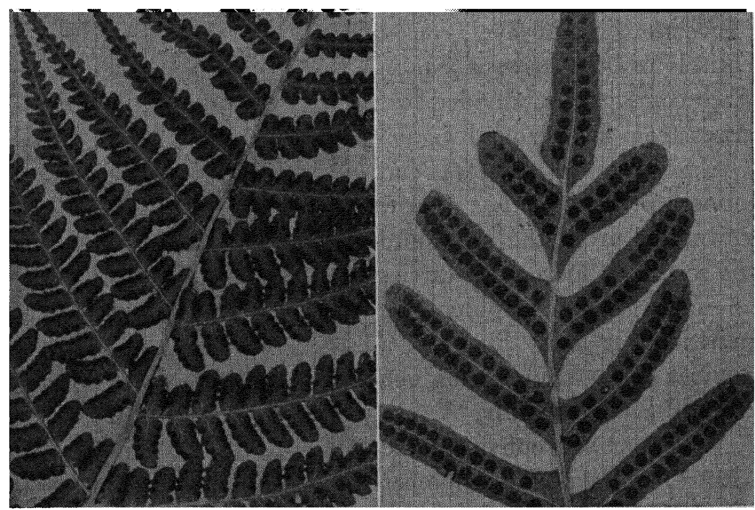
FIG. 87.—The familiar fern plant is the sporophyte generation, consisting of exposed leaves (fronds), an underground stem (the rhizome), and roots.

When the sporophyte of the fern reaches maturity a number of small, regularly arranged, dark-brown bodies (Fig. 88) appear on the under-surface of the leaves. Each brown "spot" as a whole is called a *sorus;* and when magnified, each sorus is seen to be a cluster of spore capsules, or *sporangia*. And at higher magnification one can see that each *sporangium* is a hollow structure, containing numerous *spores* (Fig. 89). While a sporangium is ripening, the spores are produced from spore mother cells, or *sporocytes*. The spore mother cell undergoes meiosis, giving rise to four haploid *spores*, each covered by a thick cell-wall. Finally when it is ripe, the sporangium bursts open, liberating the spores in large numbers (Fig. 90, C).

Usually the fern discharges its spores during dry weather,

and the wind carries the spores for considerable distances. The moisture-proof covering enables the spore to withstand exposure to dry air, which otherwise would be lethal. Eventually a spore must fall upon damp ground, if it is to germinate successfully.

The Gametophyte. When a spore germinates (Fig. 90, D), it does *not* give rise to the familiar sporophyte from which it



From Fuller, *The Plant World*

A B

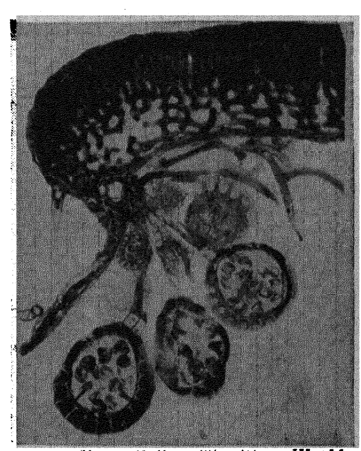
FIG. 88.—The regularly placed brown spots on the under surface of the fern leaf are *sori*, each consisting of a covered cluster of spore capsules, or *sporangia* (not visible at this magnification). A, Dryopteris marginalis. B, Polypodium scouleri.

came, but grows into the *gametophyte* of the fern. The fern gametophyte is a small, flat, heart-shaped *green* plant, called a *prothallium* (Fig. 90, E). The prothallia grow in moist shaded places on the ground, or on decaying logs; and these plants are not recognized as "ferns," except by those who have traced out their origin (Fig. 91).

The prothallium of a fern usually measures less than half an inch at the widest part. Nevertheless the prothallium grows independently like other green plants. All the cells of the prothallial *body* possess chloroplasts; but the numerous *rhizoids*, which grow down into the soil from the underside of the pro-

thallium, are colorless. During growth, the rhizoids absorb water and mineral salts for the whole prothallium; and several weeks after a spore germinates, the prothallium is sexually mature.

When mature, the gametophyte of the fern produces gametes. Both male and female organs develop on the *under* surface of each prothallium. Usually the egg-forming organs, called *archegonia*, lie near the indented margin (*apical notch*) of the prothallium (Fig. 90, E and I), and each archegonium contains a single egg. The egg lies in a hollow chamber, the *venter*, which communicates with the environment through a short tubular channel, the *neck*. The sperm-forming organs, called *antheridia*, are usually situated among the rhizoids, nearer the other end and margins of the prothallium (Fig. 90, E). Each antheridium is a hollow structure from which a number of delicate flagellated sperm are finally liberated (Fig. 90, G).



From Fuller, *The Plant World*. Courtesy of Triarch Botanical Supplies.

FIG. 89.—Magnified vertical section of a fern leaf, passing through a *sorus*. Four of the clustered *sporangia* show quite clearly; and the ripening *spores* can be seen through the side-walls of each sporangium.

The sperm are usually liberated in rainy weather, and must *swim through water*, underneath the prothallium, in order to reach the archegonia. However, the archegonia and antheridia of any one prothallium do not reach maturity at the same time, and consequently the sperm which fertilize the eggs are derived from another nearby prothallium. Many archegonia produce secretions which attract the sperm toward the eggs; and frequently a swarm of sperm will enter the neck of a single archegonium. However, only one sperm normally succeeds in penetrating the egg.

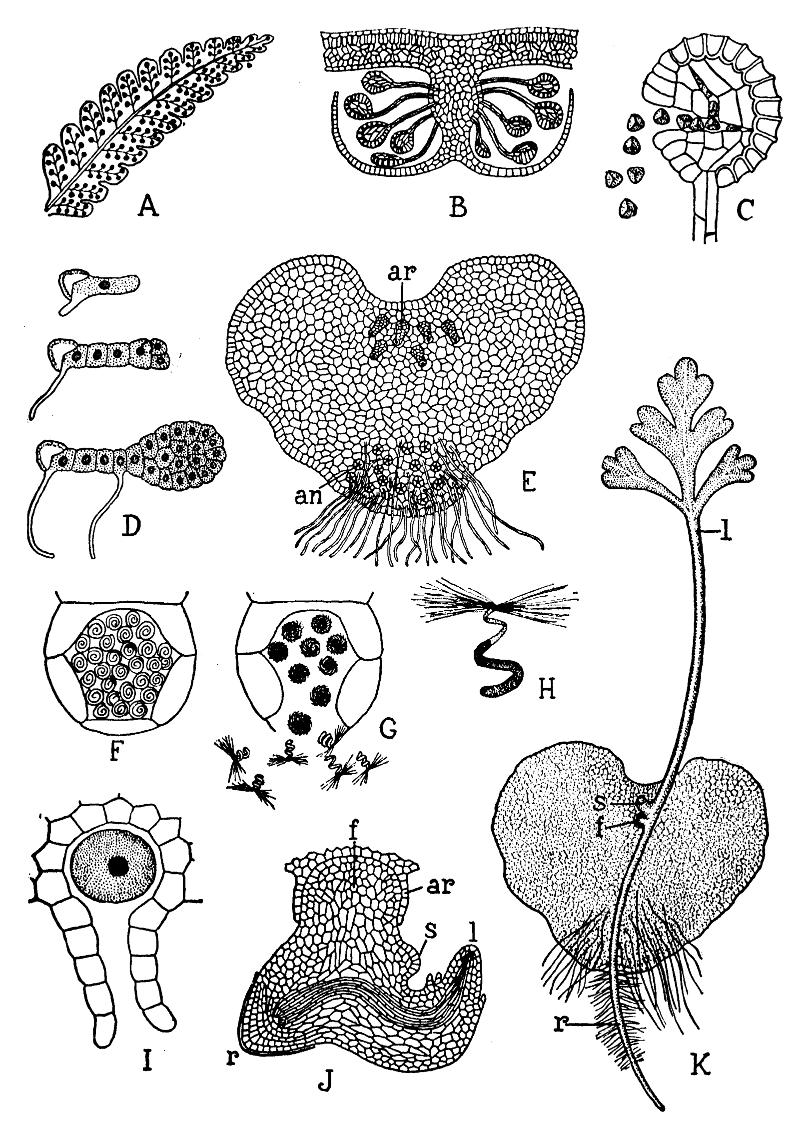


FIG. 90.—Reproduction of a fern. A, lower surface of portion of a leaf, showing sori ("fruit dots"); B, section through a sorus, showing sporangia; C, a sporangium discharging spores; D, germination of spores; E, lower surface of mature gametophyte, showing antheridia (an) and archegonia (ar); F, an antheridium (vertical section); G, antheridium discharging sperms; H, a sperm; I, a mature archegonium, showing the egg-cell (vertical section); J, embryo sporophyte, with its foot (f) embedded in the remains of the archegonium (vertical section); K, young sporophyte, still attached to the parent gametophyte; r, root; s, stem; l, leaf; f, foot.

The fertilized egg marks the beginning of a new sporophyte generation. This single diploid cell, while it still lies in the archegonium of the parent gametophyte, divides repeatedly by *mitosis*, and gives rise eventually to all the cells of the new

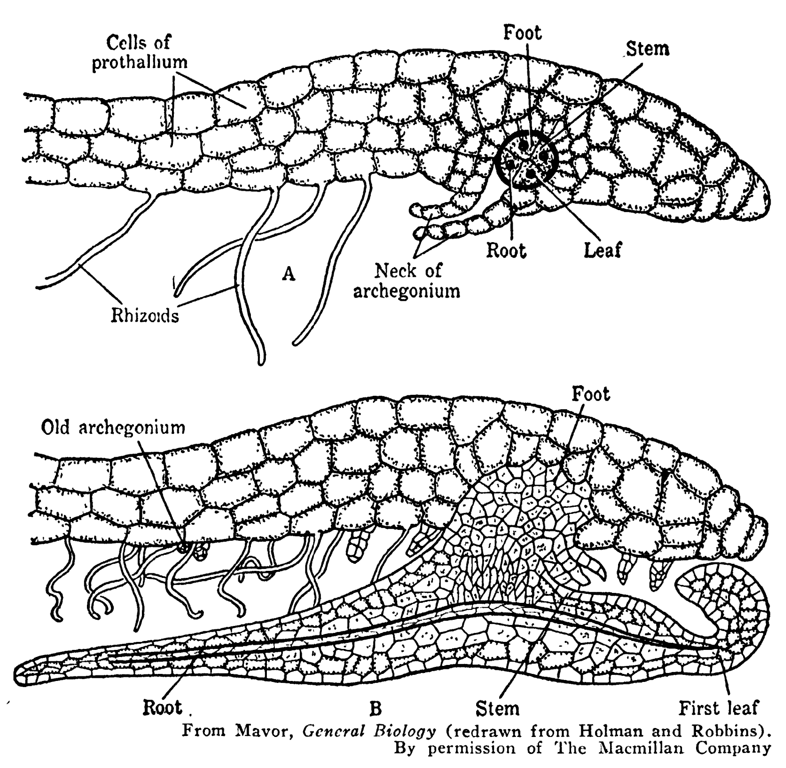


Copyright General Biological Supply House, Chicago

FIG. 91.—Hundreds of fern gametophytes (prothallia) growing on the moist wall of a small flower pot.

sporophyte (Fig. 92). During the early stages of this growth, the young sporophyte depends upon the parent gametophyte for its organic nutrients. But soon the growing sporophyte develops its own root, stem and leaf systems (Fig. 90, J-K), and thereafter the sporophyte carries on an independent holophytic nutrition. In about one year, the sporophyte reaches maturity and produces a new crop of spores—which completes the life cycle of the species.

Haploidy and Diploidy in Higher Plants. Generally speaking the foregoing life cycle is typical of *all* higher plants —as is shown in the following diagram (Fig. 93). In all higher plants the diploid zygote marks the beginning of the sporophyte



From Mavor, *General Biology* (redrawn from Holman and Robbins). By permission of The Macmillan Company

FIG. 92.—Early development of the sporophyte in the archegonium of the gametophyte of a fern. A, four-cell stage, in which the cells which give rise to the main parts of the young sporophyte are already determined; B, an older sporophyte, still attached to the gametophyte.

generation; and since the cells of the sporophyte are all derived by *mitosis* from this diploid cell, all the cells of the sporophyte generation are diploid. In the sporangia, however, the spores arise by *meiosis,* from spore mother cells; and each haploid spore represents the beginning of the gametophyte generation. Each spore produces all the cells of the gametophyte by *mitosis,* and consequently all the cells of the gametophyte remain hap-

loid. Higher plants, therefore, differ from higher animals in that the gametes of the plant arise by *mitosis* from the haploid cells of the gametophyte; or to state the matter differently, plants have developed a haploid generation which intervenes between meiosis and fertilization (Fig. 93).

Life Cycles in Relation to the Classification of Plants. The five main branches, or *phyla*, of the *plant kingdom* embrace a multitude of species; but all members of any one

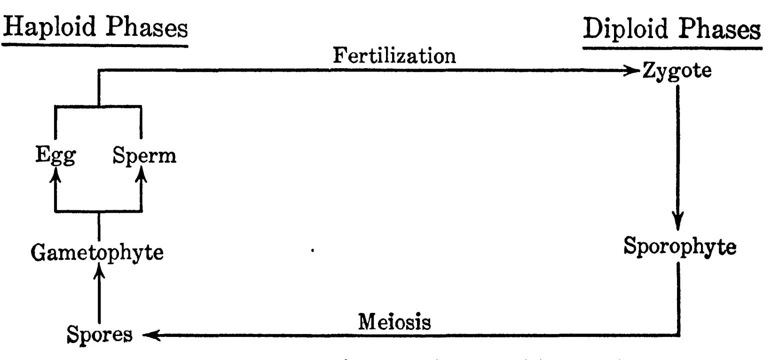


FIG. 93.—Generalized life cycle of a typical higher plant.

phylum have inherited the same general pattern of structure and function. In the following *classification of the plants,* the life cycles are given special emphasis, although numerous other characteristics are also mentioned.

I. *Phylum Schizophyta* (literally, the fission-plants; 3,000 species).

The modern Schizophytes are represented by the *bacteria* and *blue-green* algae. These primitive plants display *no form of sexual reproduction.* Schizophytes reproduce *by binary fission* (p. 59), although quite a few species also form spores. None of the Schizophytes are truly multicellular, i.e., all are either unicellular or colonial. Essentially the Schizophytes are *aquatic* plants, although many species live in moist places, such as damp soil; and many species are parasitic. No sharp distinction between nucleus and cytoplasm has been developed in the cells of a majority of these primitive organisms.

II. *Phylum Thallophyta* (literally, thallus-plants; 80,000 species).

Many Thallophytes possess chlorophyl (green, red and brown algae); but others (yeasts, molds, rusts, smuts, mushrooms, etc.) lack this green pigment. Some Thallophytes are truly multicellular, although many species remain unicellular or colonial. The cells of Thallophytes display distinct nuclei; and practically all Thallophytes have developed some form of sexual reproduction to supplement the asexual methods. But a *regular alternation of sexual* (*gametophyte*) and *asexual* (*sporophyte*) generations is not generally characteristic of the group. Thallophytes have remained essentially aquatic plants, although many parasitic and saprophytic species have been evolved. The body structure is simple, without true roots, stems or leaves (thallus type of body).

III. *Phylum Bryophyta* (literally, moss-plants; 17,000 species).

The Bryophytes, which include the *mosses* and the *liverworts*, are the simplest of the *land* plants. All Bryophytes display *a regular alternation of sexual and asexual generations*. Among Bryophytes, however, the *gametophyte is the dominant form of the plant*, and the *sporophyte* is nutritively *dependent* upon the gametophyte (see later). Adaptation to the land is not very complete. The mosses have developed a very simple leaf and stem system, but possess rhizoids in place of *true roots*. The liverworts, or most primitive Bryophytes, usually have a thalloid body, devoid of any root, stem, or leaf system.

IV. *Phylum Pteridophyta* (literally, fern-plants; 5,000 species).

The Pteridophytes, which include all ferns, "club-mosses" and horse-tails, are fairly well adapted to land conditions. All Pteridophytes have true root-stem-leaf systems, equipped with well-developed *vascular* (distributing) tissues (see later). Pteridophytes have a *regular alternation of generations*, but the *sporophyte* is dominant relative to the *gametophyte*. Both the gametophyte and sporophyte grow independently in a holophytic manner.

V. *Phylum Spermatophyta* (literally, seed-plants; 130,000 species).

The seed-bearing plants include a countless variety of conifers, cycads and *flowering* plants. Among the Spermatophytes, a highly vascularized root-stem-leaf system gives an excellent adaptation to terrestrial conditions. Also the reproductive cycle of the Spermatophytes is very well adapted to the land habitat. In the *regular alternation of generations*, the sporophyte has become entirely dominant, and the gametophyte, which is reduced to microscopic dimensions, has become entirely dependent upon the parent sporophyte (see later).

The Life Cycle in Various Thallophytes. Sexual reproduction appears first among the Thallophytes, but these primitive plants do not adhere to any standard type of life cycle. The commonest type of cycle is exhibited by Spirogyra (p. 64), and Oedogonium (Fig. 94). In both these algae, the colony is composed of haploid cells; and any cell of the filament can give rise to one or more gametes. Accordingly these plants are equivalent to the gametophyte generation in the higher plants. However, no sporophyte generation can be recognized, because the zygote divides *meiotically* as soon as it begins to germinate, and all the cells of the new filament are haploid (Fig. 94, D-H).

The opposite type of cycle is found in *Fucus* (Fig. 95) and a few other *brown algae*. The body cells of this multicellular seaweed are all diploid, and only the gametes are haploid. The sperm and eggs respectively are formed by *meiosis* in hollow structures found at the ends of many of the branches of the sexually mature plants. After fertilization, which occurs when the gametes are extruded into the sea water, the diploid zygote multiplies *mitotically*, forming all the cells of the new individual.

An irregular alternation of generations, foreshadowing the reproductive habits of higher plants, occurs in a few Thallophytes—as in the bread mold, Rhizopus (p. 234). The spores of the mold are haploid, and in a suitable medium, such as moist bread, each haploid spore grows into a mycelium, called

the *haplomycelium* (Fig. 96, I). In the sporangia of the haplomycelium, the spores are formed, *not by meiosis* as in most other plants, but by *mitosis*—and this asexual type of reproduction

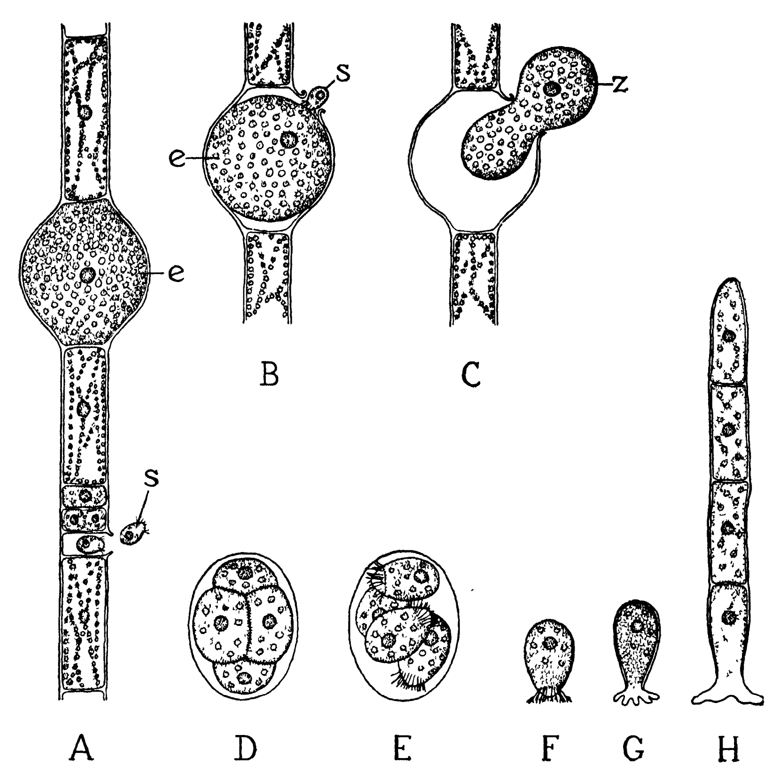
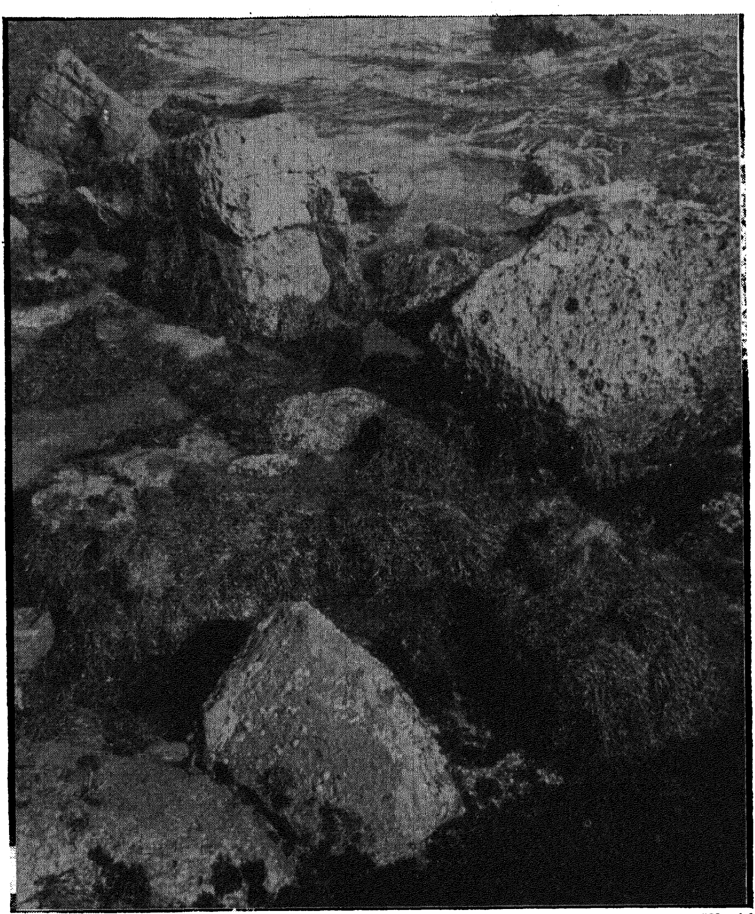


FIG. 94.—Reproduction of Oedogonium, a filamentous green alga. A, portion of a mature filament, showing development of sperm-cells (s) and egg-cell (e); B, fertilization; C, liberation of the zygote (z); D, E, division of the zygote into four spores; F-H, development of one of these spores into a new filament.

may continue for many generations. However, on rare occasions, Rhizopus also reproduces sexually. In this case, gametes are formed on two neighboring mycelia, and these fuse to form a diploid zygospore (Fig. 96, II). This zygote is very resistant to unfavorable conditions. But when a favorable environment is found, the zygospore gives rise by mitosis to a new mycelium, called the *diplomycelium*, because all the nuclei are diploid.

The diplomycelium eventually develops its sporangium, which contains diploid spore mother cells, or sporocytes. *In the diplomycelium* (Fig. 96, II), *the spores are formed by meiosis;* and,

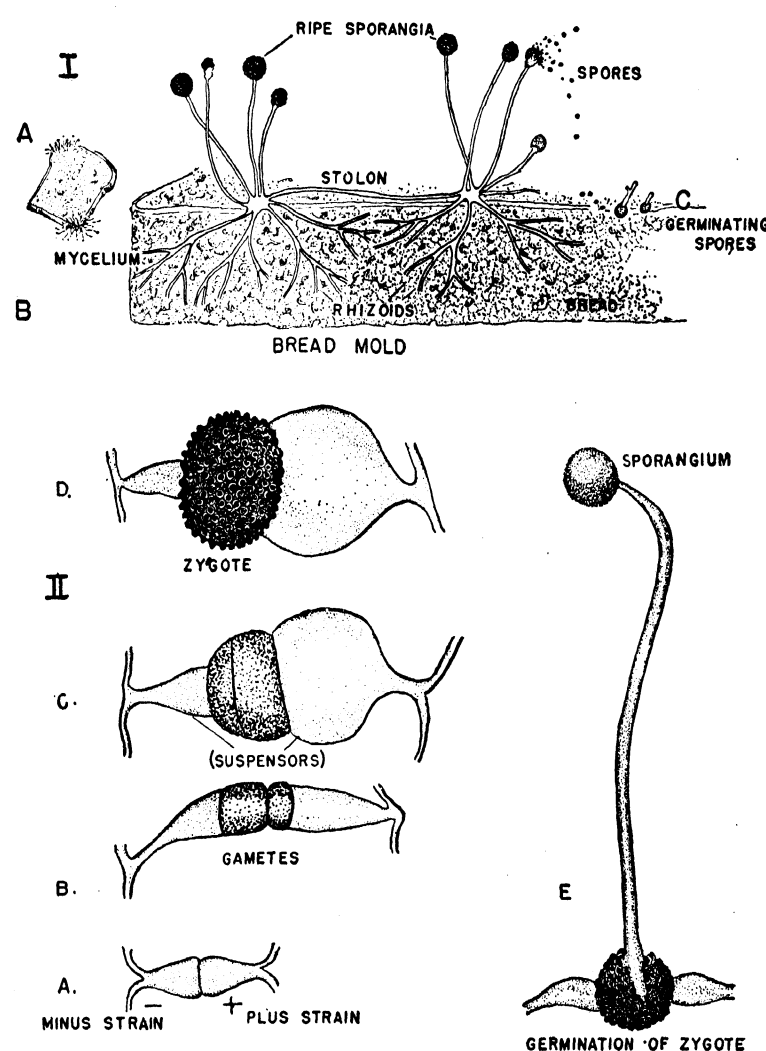


From Fuller, *The Plant World*

Fig. 95.—Rockweed (Fucus) growing on intertidal rocks. California coast.

after liberation, each haploid spore gives rise to a new haplomycelium.

The haplomycelium, since it is haploid and forms gametes, is equivalent to a gametophyte generation; and the diplomycelium, since it is diploid and reproduces by sporulation, represents

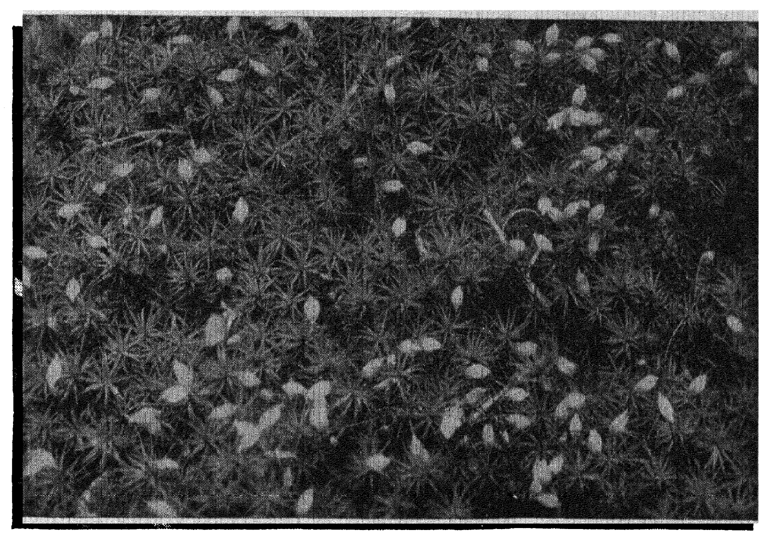


From MacDougall and Hegner, *Biology*, by permission of McGraw-Hill Book Co., Inc.

FIG. 96.—I. Bread mold (Rhizopus nigricans). A, Bread mold growing on bread. B, Enlarged portion of mature plant showing plant body and sporangia. II. Sexual cycle in the bread mold. If plus and minus strains grow in the same situation, the tips of the aerial hyphae will come together, fuse, and form a zygote. When mature, the zygote germinates and a new plant begins its growth. (L. Runyon.)

the sporophyte. However, the cycle in Rhizopus is irregular, since fertilization occurs only rarely, and since the gametophyte generation retains a capacity to reproduce by sporulation.

Life Cycle of the Mosses. Mosses, the most familiar Bryophytes, are small, green, *leafy* plants, which grow in densely



Photograph by L. W. Brownell

FIG. 97.—A clump of moss plants (Polytrichum). The leafy (lower) part of each plant is a gametophyte, from the top of which grows the slender-stalked *sporophyte.* The conspicuous white spindle-shaped bodies are the *sporangia* of the sporophytes.

crowded masses, on damp and shaded soils (Fig. 97). Mosses are not well adapted to terrestrial conditions, and most species cannot survive in dry localities. Most mosses are relatively short plants, with an average height of only about half an inch.

The small green leafy-stemmed moss plant is a gametophyte, i.e., a haploid gamete-producing individual. The crowded *leaves* all originate from a single central stem, which cannot be seen unless the leaves are plucked away. Numerous *rhizoids* extend down into the soil from the lower end of the stem. The rhizoids absorb water and inorganic salts for the upper green parts of the plant, which, in return, provide the rhizoids with glucose.

Accordingly, the gametophyte of the moss is a small but independent plant, which displays a typically holophytic nutrition.

The *antheridia,* or *archegonia,* depending upon the sex of the gametophyte, develop at the top of the stem, hidden by the encircling upper leaves (Fig. 98, A and E). In mature female plants, a single large egg cell is found in the venter of each archegonium (Fig. 98, F). The sperm are liberated in swarms (Fig. 98, C) from the antheridia (Fig. 98, B) of the male plants, during periods of rain, or heavy dew. Each sperm is a delicate elongate cell possessing two flagella, which enable the sperm to swim through water to a neighboring female plant. Some sort of chemical attraction appears to emanate from the neck of the archegonium, and thousands of sperm may simultaneously attempt to swim down this narrow passage. However, only one sperm usually participates in fertilization, which occurs in the venter chamber.

The fertilized egg marks the inception of the sporophyte generation. Shortly after fertilization this diploid cell starts its development inside the archegonium of the female plant. A series of mitotic divisions leads to the formation of an elongate mass of cells (Fig. 98, G), which is the very young embryo sporophyte. The lower end of the embryo sporophyte, which is called the *foot,* grows downward into the stem of the parent gametophyte, where it becomes firmly attached. The upper end of the embryo grows more or less vertically into a long slender *stalk,* at the top of which a hollow *sporangium* finally appears (Fig. 98, H). The early stages of this growth occur entirely within the archegonium which enlarges accordingly (Fig. 98, G). But finally the stalk grows so rapidly that it tears the neck, which is carried aloft on the sporangium above the upper leaves of the female gametophyte.

The whole sporophyte—consisting of foot, stalk and sporangium—remains permanently attached to the apex of the female gametophyte (Fig. 98, H). The exposed cells of the stalk and spore-capsule may contain some chloroplasts and perform some photosynthesis; but the sporophyte obtains most of its

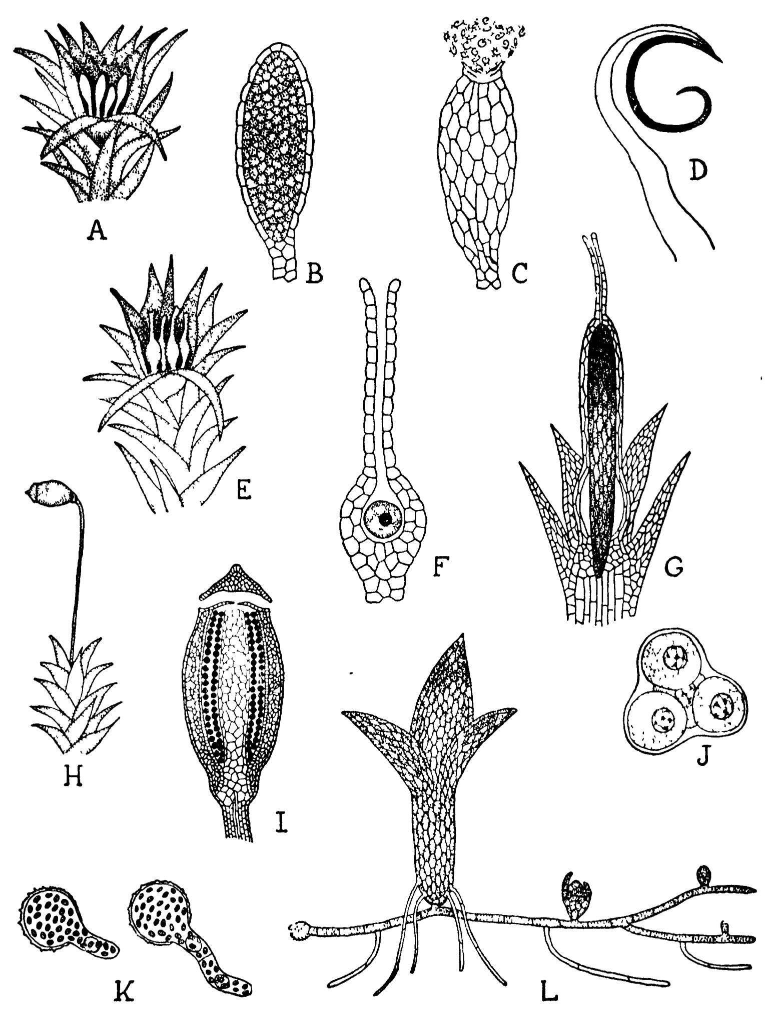


FIG. 98.—Reproduction of the mosses. A, tip of male gametophyte, showing antheridia; B, an antheridium (vertical section); C, antheridium discharging sperms; D, a sperm; E, tip of female gametophyte, showing archegonia; F, a mature archegonium, showing the egg-cell (vertical section); G, embryo sporophyte developing within the archegonium and pushing its foot down into the tissues of the gametophyte (vertical section); H, mature sporophyte, attached to the tip of the female gametophyte; I, spore capsule (vertical section), showing spores (black), lid which falls off when the capsule is ripe, and teeth which open to liberate the spores; J, division of a sporocyte into four spores; K, germination of spores; L, protonema with buds developing into leafy stems.

nourishment from the gametophyte by absorption through the foot.

At maturity many spore mother cells, or sporocytes, are formed in the sporangium. Each of these diploid cells eventually produces four spores, by *meiosis;* and later, when the lid of the sporangium (Fig. 98, I-J) drops off, a multitude of tiny haploid spores are discharged into the dry atmosphere.

As in other higher plants, the spore represents the beginning of the gametophyte generation. In the mosses, however, more than one gametophyte may arise from one spore, if it happens to fall in a favorable locality. When the spore germinates, it bursts its protective cover and begins to divide rapidly by mitosis (Fig. 98, K). Initially this produces a branching filament which closely resembles some of the green algae, from which the mosses presumably have arisen. In the moss this young gametophyte is called a *protonema;* and each protonema may give rise to several erect leafy gametophytes by a process of budding (Fig. 98, L). Finally the protonema dies off, isolating the several erect leafy gametophytes, which soon mature and produce the gametes of the next generation.

Summary: The Life Cycles of the Moss and Fern. In summary, the life cycle of the moss and other Bryophytes displays a clear *general* resemblance to the cycle of the fern and other Pteridophytes. In both cases: (1) the haploid sexual gametophyte alternates regularly with the diploid asexual sporophyte; (2) the haploid spores are resistant to dryness, and are well adapted for dissemination through the atmosphere; and (3) the sperm require an abundance of water in order to reach the eggs. However, the gametophyte, which is dominant in the Bryophytes, is relatively inconspicuous in the Pteridophytes, although the fern gametophyte still carries on an independent nutrition. The sporophyte, on the other hand, which is relatively inconspicuous and dependent in Bryophytes, is the dominant independent generation in Pteridophytes. These evolutionary tendencies continue—reaching a maximum in the seed plants. Among seed plants, the gametophyte generation is further reduced, to microscopic dimensions, and the gametophyte is com-

pletely dependent on the large dominant sporophyte. This development has enabled the Spermatophytes to spread to much drier regions of the earth, since the sperm are free of the necessity of swimming through water on their journey toward the eggs (see later).

Life Cycle of Selaginella, Another Pteridophyte. Selaginella and a few other Pteridophytes show transitional developments which foreshadow a further reduction of the gametophyte, such as occurs in all seed plants. The sporophyte of Selaginella (Fig. 99) has a profusely branched creeping stem, with short erect branches and small scalelike green leaves. The sporangia are borne in conelike structures at the tips of the erect branches (Fig. 99, A). But unlike most other Pteridophytes, Selaginella has two kinds of sporangia: (1) *microsporangia,* in which the spores (*microspores*) are relatively small; and (2) *macrosporangia,* in which the spores are about a hundred times larger (Fig. 99, B-C).

When shed, each *microspore* develops into a very small (microscopic) *male* gametophyte, which lacks chlorophyl, and consists mainly of a single antheriderium (Fig. 99, D-G). This growth occurs inside the protective cover of the microspore, at the expense of organic substances already present in the spore at the time of shedding. Meanwhile, the macrospore develops into a *female* gametophyte, which also lies mainly inside the old spore casing (Fig. 99, I). When mature, the female gametophyte displays several poorly differentiated archegonia, each containing a single egg cell. The female gametophyte has very little chlorophyl, and is dependent for its growth upon substances initially present in the macrospore.

The many sperm, which are liberated from the male gametophyte swim in the soil water, and each may succeed in fertilizing an egg. The zygote gives rise to the young sporophyte which at first grows inside the female gametophyte, at the expense of organic materials present in the gametophyte cells (Fig. 99, J). Finally, however, the sporophyte develops its own root-stem-leaf system and becomes an independent, self-sustaining plant (Fig. 99, K).

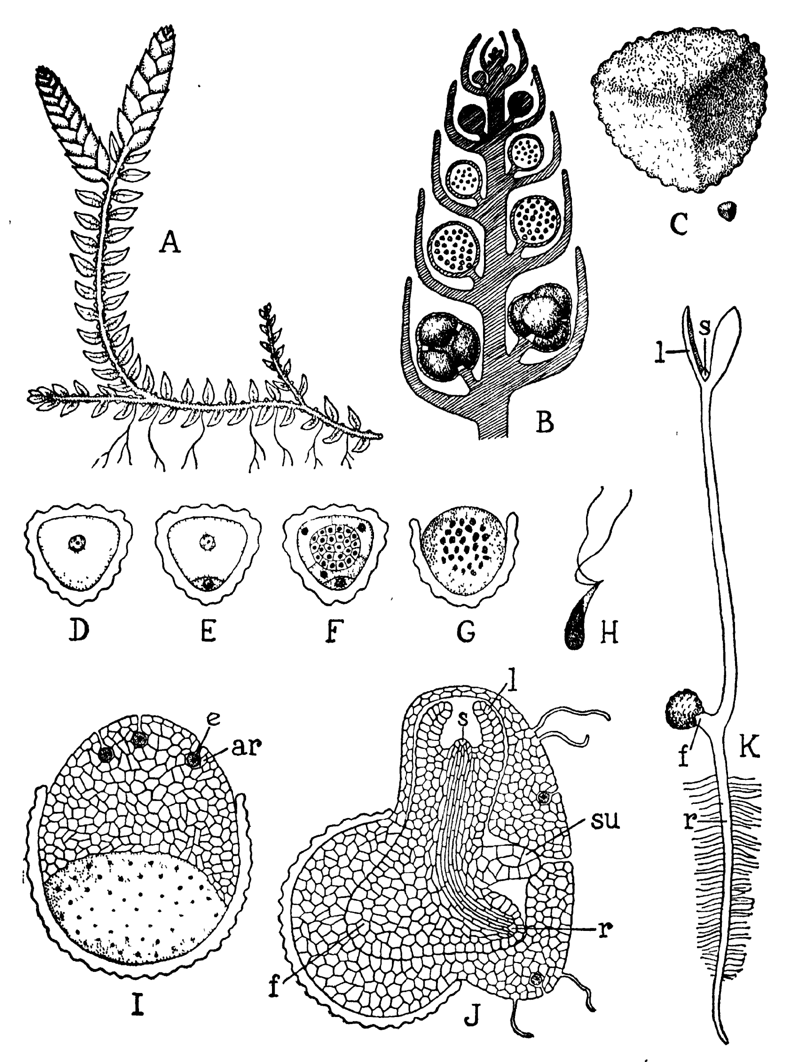


FIG. 99.—Reproduction of Selaginella. A, portion of sporophyte, showing fruiting cones; B, portion of a fruiting cone (vertical section), showing macrosporangia below and microsporangia above; C, a macrospore and a microspore, showing their relative sizes; D-G, development of male gametophyte within the microspore wall (vertical sections); H, a sperm; I, female gametophyte within the macrospore wall (vertical section), showing archegonia (ar) and egg cells (e); J, embryo sporophyte developing within the archegonium; K, young sporophyte, still attached to the female gametophyte, which is still within the macrospore wall; f, foot; r, root; s, stem; l, leaf; su, suspensor.

In Selaginella and other club-mosses, the gametophyte has lost the status of an independent plant. It is reduced to a mere reproductive mechanism which, however, assures the species of fertilization and bi-parental inheritance. The sturdy land-adapted sporophyte provides the gametophytes with a food supply adequate for the production of gametes, and thus the hazards experienced by a poorly adapted gametophyte are reduced. This eliminates one vulnerable feature of the Pteridophyte cycle, which has tended to prevent the spread of these organisms to drier regions of the earth. But only among the Spermatophytes has another vulnerability of the cycle been eliminated, since Selaginella still requires a water-flooded soil at the time when the delicate sperm are swimming to the eggs.

Life Cycle of the Seed-plants. The Spermatophytes, or seed-bearing plants, are by far the most successful group in the plant kingdom. All common trees, shrubs, grasses, weeds and "garden plants" are Spermatophytes. In number of species Spermatophytes far exceed all other plants combined, even though their evolutionary history—as indicated by the absence of Spermatophyte fossils in all earlier geological formations—has been a comparatively short one. The Spermatophytes are exceedingly well adapted to land conditions, and some species have spread to virtually all habitats.

The formation of *seeds* is common to all Spermatophytes. A seed, essentially, is a dormant embryo sporophyte, protected by several enveloping tissues. But the true nature of seeds, and the importance of seeds in the evolutionary success of the Spermatophytes, can be appreciated only in relation to the life cycle (see later).

Gymnosperms vs. Angiosperms. The phylum Spermatophyta is subdivided into two large subphyla:

I. *Gymnospermae* (literally, naked-seeds).

The Gymnosperms include the pines, spruces, hemlocks, ginkos, cycads, and all other plants having seeds which are formed in *cones* (rather than true flowers), and seeds which are not contained within an ovule chamber (see below).

II. *Angiospermae* (literally, covered-seeds).

The Angiosperms include a wide variety of trees, shrubs, grasses, and all other plants possessing true flowers, and seeds which develop inside of the capsular *ovule chamber* of the flower.

The Gymnosperms, while less numerous in species than Angiosperms, show more variability in the reproductive cycle. In fact the Gymnosperms exhibit many transitions between the rather primitive cycle of Selaginella (p. 239), and the well-established cycle of the Angiosperms. But it is necessary to pass over these transitional types and to deal mainly with the flowering plants (Angiosperms), which make up a great majority of familiar plants, especially in temperate zones.

The Sporophyte Generation. Among Angiosperms the whole visible plant—consisting of roots, stem, leaves, and flowers—represents the sporophyte generation. The sporophyte varies in size in different species, from the tremendous bulk of larger trees to the inconspicuous size of many grasses. But both the male and the female gametophytes of the Angiosperm are reduced to microscopic dimensions. In fact these haploid sexual stages are only found by dissecting into the tissues of the *flower*. In the flower the gametophytes receive protection and nourishment during the critical period when the eggs and sperm are formed, and while fertilization is occurring.

The Flower. A *flower* represents an organized group of modified leaves, which fulfills the reproductive functions of the plant. A *complete* flower displays four distinct kinds of modified leaves, arranged in concentric *whorls*, attached to a *receptacle*, which connects the flower with its stalk (Fig. 100, 10). The outermost whorl, called the *calyx*, consists of separate parts, the *sepals* (Fig. 100, 9), which are usually leaflike in form and color. Just inside the calyx lies the *corolla*, the separate parts of which are called the *petals* (Fig. 100, 8). The petals also display a leaflike form, but often they are brightly colored, especially in insect-pollinated species. The petals and sepals are subject to endless variation in form, color and number, and either

or both may be entirely absent, since they play a very indirect role in reproduction.

Just inside the petals come the *microsporophyls*, which commonly are called the *stamens* (Fig. 100, 3). Each stamen consists of a slender *filament* which bears an *anther* at the upper end. Essentially the anther is a group (usually of 2 or 4) of pollen capsules (*microsporangia*) in which the pollen grains

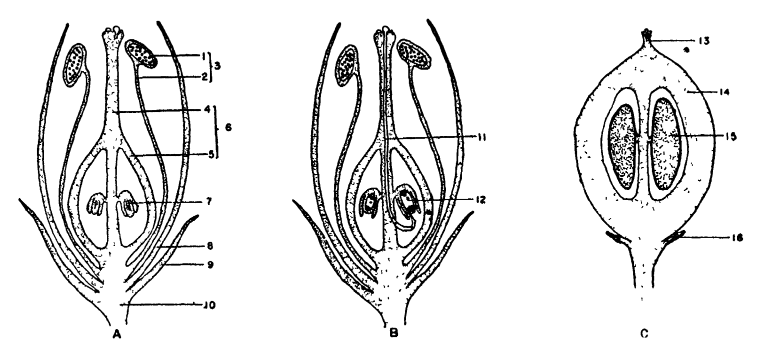
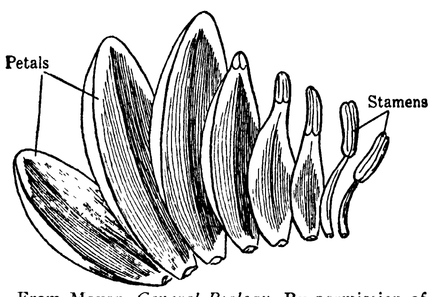


FIG. 100.—Stages in the life cycle of an Angiosperm. A, flower, just after pollination (1, microspores in the microsporangium, or anther; 2, filament; 3, stamen; 4, style; 5, ovule case; 6, pistil; 7, macrospore in an ovule; 8, petal; 9, sepal; 10, receptacle); B, flower, sometime after pollination (11, male gametophyte; 12, female gametophyte); C, the fruit of same flower (13, withered remnant of the style; 14, enlarged wall of the ovule case; 15, a seed; 16, withered remnant of the petals and sepals).

(*microspores*) are produced in great numbers. In form the anthers are so highly modified as to be quite unrecognizable as leaves (Fig. 101). This is also true of the *macrosporophyls* (commonly called the *carpels*) which make up the innermost whorl, at the very center of the flower. In most flowers the carpels are united, partially or completely, to form a single compound organ called the *pistil* (Fig. 100, 6). Typically the pistil consists of an enlarged hollow basal part, the *ovule chamber*, surmounted by a slender cylinder, the *style*, which terminates in a moist sticky part, the *stigma*. Inside the ovule chamber one finds one or more ovules (*macrosporangia*), in which the macrospores are formed.

The flowers of different species exhibit many variations (Figs. 102-104). Usually both stamens and pistils are present, but

some plants possess two kinds of incomplete flowers: one containing only stamens (*staminate flowers*), and the other containing only pistils (*pistillate flowers*). These kinds of flowers may be borne on the same, or upon separate individual plants. Plants bearing only staminate flowers may be referred to as male, and those with only pistillate flowers as female plants; but in either case, the sporophyte plant does not give rise directly to the sperm or eggs.



From Mavor, *General Biology*. By permission of The Macmillan Co.

FIG. 101.—Transition from petals to stamens in the white water lily. (Redrawn after Asa Gray.)

Essential Nature of the Floral Parts. The essential nature of the floral structures is difficult to comprehend, except in comparison with equivalent structures in the non-flowering plants. The *ovules*, which develop in the ovule chamber, are equivalent to the sporangia of other plants, or more specifically, to the *macrosporangium* of Selaginella. In seed plants, however, only one macrospore is formed in each *ovule* (macrosporangium). This single large haploid cell is formed by meiosis from a macrospore mother cell (*macrosporocyte*), and lies near the center of the ovule (Fig. 100, 7). During the two divisions of meiosis most of the cytoplasm is retained by one of the four daughter cells, and this cell becomes the functional *macrospore*. The macrospore lies in direct contact with three smaller sister "spores" (Fig. 105, H), but the three smaller cells are sterile. Eventually they disintegrate and do not play any further part in reproduction.



From Fuller, *The Plant World*

FIG. 102.—Tulips are monocotyledons. Note the 3 sepals, 3 petals, 6 stamens, and compound pistil with a 3-branched stigma.





From Fuller, *The Plant World*

A B

FIG. 103.—A, Flower of amaryllis, a monocotyledon, showing 3 sepals, 3 petals, 3-branched stigma, and 6 stamens. B, Close-up of stamens and stigma of amaryllis flower.

The Gametophytes of the Angiosperm. Like the spores of other plants, the *macrospore* is a haploid cell which is destined to develop into a gametophyte—in this case the *female gametophyte* of the species. But the female gametophyte of the seed plant never attains anything but a microscopic size. At maturity it consists of only eight cells, including the *egg cell* and the



From Fuller, *The Plant World*

FIG. 104.—The flowers of peonies are considered primitive. Notice the numerous stamens and the separate, simple pistils in the center of each flower.

two *endosperm nuclei* (Fig. 105, L). The diminutive female gametophyte lies near the center of the ovule, protected and nourished by the surrounding tissues, and is not exposed to the hazards of an external environment (Fig. 100, 12). Finally the single egg cell matures and must await fertilization before further development can occur.

Meanwhile the pollen grains (microspores), after liberation from the anthers, may light on the stigma (Fig. 100) of the same flower (*self-pollination*), or more frequently, they are carried by wind or insects to the stigma of another plant (*cross-pollination*). The pollen grains (microspores) are haploid cells,

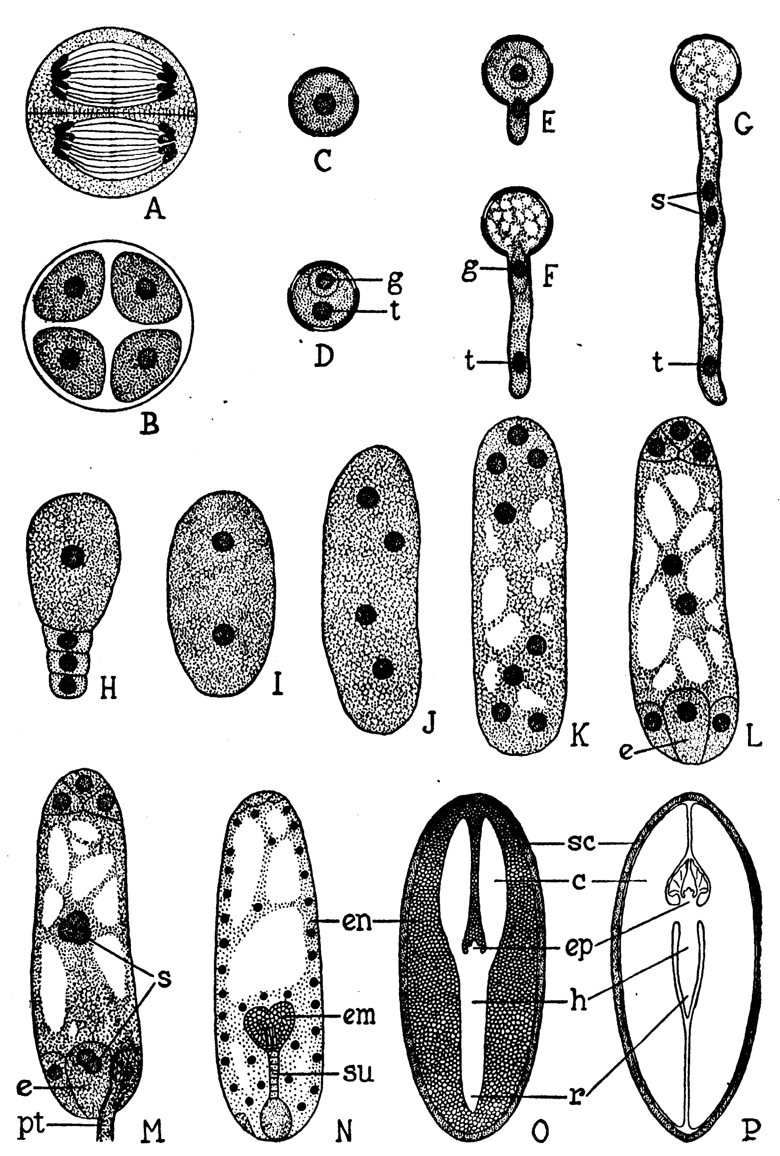


FIG. 105.—Reproduction of angiosperms. A, B, division of microsporocyte into four microspores (pollen grains); C-G, development of microspore into male gametophyte; t, tube nucleus; g, generative nucleus; s, sperm nuclei. H, the macrospore and its three sterile sister cells; I-L, development of macrospore into female gametophyte; e, egg cell. M, fertilization; pt, pollen tube; s, sperm nuclei. N, development of embryo (em) and endosperm (en); su, suspensor. O, a mature seed with endosperm; P, a seed without endosperm; c, cotyledon; h, hypocotyl; ep, epicotyl; r, radicle; sc, seed coats.

which are formed in the anthers as a result of meiosis, from diploid microspore mother cells (microsporocytes). Each pollen grain is destined to grow into a gametophyte—in this case, a *male* gametophyte. Such a development normally occurs only when the microspore falls into the sugary secretion of a stigma of the same species, although pollen grains can often be induced to germinate in artificial solutions. The male gametophyte, which is commonly called the pollen tube, now grows downward through the tissues of the stigma and style, deriving nourishment and protection from these tissues (Fig. 100, 11). At maturity, when it penetrates an ovule and approaches the egg cell, the male gametophyte consists of only three cells—or rather it consists of a trinucleate syncytium (Fig. 105, G). One of the three nuclei is the *tube nucleus*, which regulates the growth of the pollen tube; and the other two are sperm nuclei. One of these sperm nuclei unites with the egg, forming the zygote, while the other unites with both the endosperm nuclei, forming a *triploid endosperm cell* (Fig. 105, M).

Significance of the Gametophytes. The intrinsic nature of the pollen tube could not be appreciated, were it not for the occurrence of equivalent stages in lower plants. The pollen tube is regarded as a male gametophyte because (1) it arises from a spore, (2) consists of haploid cells, and (3) gives rise to sperm. On similar grounds, the small female gametophyte of the seed plant is also identified as such. In seed plants, the vigorous land-adapted sporophyte harbors and nurtures the gametophytes, protecting them from the hazards of independent life; and the gametophytes are reduced to the simplest condition, although still they are capable of fulfilling their essential functions. In this way the Spermatophytes have adapted their life cycle to conditions as they exist in the land environment. The male and female gametophytes develop in close proximity to each other, protected by the tissues of the parent sporophyte. Under these conditions fertilization can occur even in very dry regions, where the water available in the external environment is so scant that free-swimming sperm would not be able to reach the eggs. Accordingly, Spermatophytes have been able to spread to drier

parts of the earth, where more primitive plants, handicapped by the aquatic type of fertilization, cannot survive. In the life cycle of the seed plants, the burden of carrying the paternal chromosomes to the egg is shifted from the sperm, which are ill-adapted to land conditions, to the spores, which even in primitive plants are very resistant to the dry conditions of the atmosphere. The thick-walled pollen grains are produced in very large numbers, and this makes it likely that some will be carried, usually by air—but sometimes by insects, or water—from an anther to the stigma of the same species.

The Embryo Sporophyte, the Seed and the Fruit. Fertilization occurs when a sperm nucleus leaves the pollen tube (male gametophyte), and fuses with an egg nucleus (Fig. 105, M). The penetration of the sperm into the egg is facilitated by the fact that the intervening cell walls are "digested away" when the end of the pollen tube comes in contact with the egg cell. As in other plants, the zygote soon develops into a new sporophyte. The zygote multiplies by mitosis, and, growing at the expense of the surrounding endosperm tissue, it produces a mass of diploid cells which represents the embryo sporophyte (Fig. 105, M-P).

While the embryo is growing, many changes also occur in the several tissues surrounding the embryo: (1) the endosperm cell gives rise to a mass of endosperm tissue, which lies in direct contact with the embryo and provides it with organic food; (2) the ovule, taken as a whole, becomes the seed; and (3) the ovule chamber, also taken as a whole, enlarges and becomes the *fruit* (Fig. 100, C). Accordingly the *embryo sporophyte* (Fig. 105, O-P) lies near the center of the ripe seed, surrounded by an endosperm, unless this tissue is used up before the seed is ripe. In the seed, however, the only body of cells which arises from the fertilized egg is the embryo itself; and only these diploid cells are represented in the body of the mature sporophyte, which develops after the seed has sprouted.

The Seed. Seeds are entirely distinctive of the members of the phylum Spermatophyta. *A seed is a dormant embryo sporo-*

phyte, enclosed in a cover which is derived chiefly from the outer wall of the ovule. Some seeds also contain gametophyte tissue (the endosperm), directly surrounding the embryo and separating the embryo from the seed cover (Fig. 105, O). But in most seeds, all the substance of the endosperm is absorbed by the growing embryo during the period of ripening, leaving no trace of endosperm in the mature seed (Fig. 105, P).

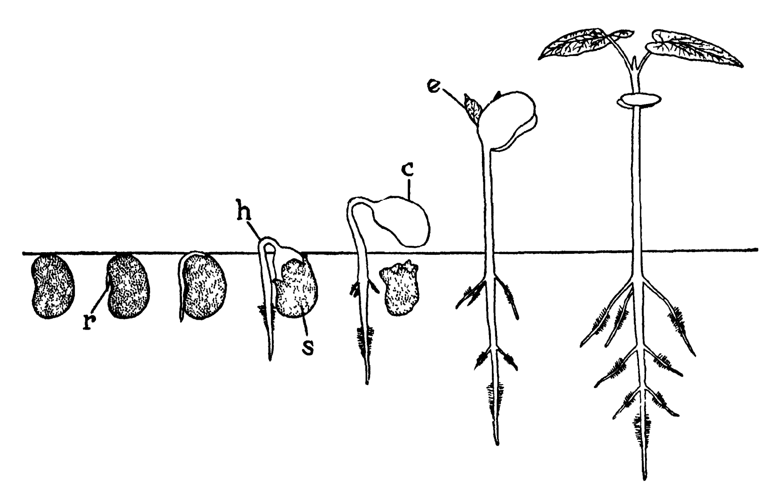
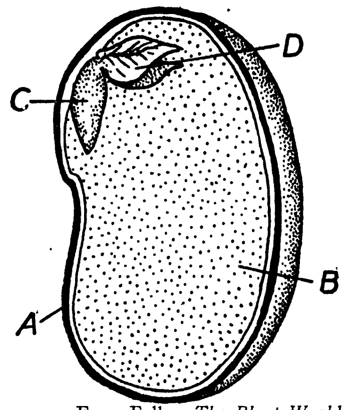


FIG. 106.—Germination of a seed (bean). s, seed coats, r, radicle, h, hypocotyl; c, cotyledon; e, epicotyl.

Seeds have played an important role in permitting the seed plants to scatter themselves over wide areas of the earth. The dormant embryo within some seeds may survive for more than a hundred years, and is able to endure adverse conditions of dryness, temperature, etc. Many seeds are equipped with devices (wings, spines, etc.) which play a part in successfully dispersing the species. Moreover, because the embryo has reached a fairly advanced stage of development in the ripe seed, and because rapid growth is assured by organic food stored in the seed, the new sporophyte very quickly establishes itself as a sturdy independent plant soon after the seed falls upon new ground, where conditions are right for sprouting (Fig. 106).

Structure of the Embryo; the Cotyledons. When the protective coat of a bean seed is removed, the embryo as a whole is exposed. The main bulk of the embryo consists of the *two cotyledons*, i.e., the two swollen fleshy "halves of the bean." But between the cotyledons, and not fully visible until one cotyledon is removed, lies the *body* of the embryo (Fig. 107).

The *cotyledons* are the *storage leaves* of the embryo. The swollen fleshiness of these embryonic leaves is due to large amounts of starch and other organic compounds contributed to the cotyledons by the endosperm and other surrounding tissues, while the seed is ripening. Such a reserve of organic matter is vitally important to the embryo, when the seed begins to sprout. Until the young sporophyte develops a good root system and raises its stem and leaves above ground where light is available, it cannot synthesize its own organic materials and grow in a self-sufficient manner. During the first rapid growth of the young sporophyte, the cotyledons gradually give up their content of organic material, passing it to the growing body of the plant. Consequently the cotyledons keep shrinking as the seedling grows. In most seedlings the withered cotyledons finally drop off, but then the young sporophyte is no longer called a *seedling*—it is an independent plant.

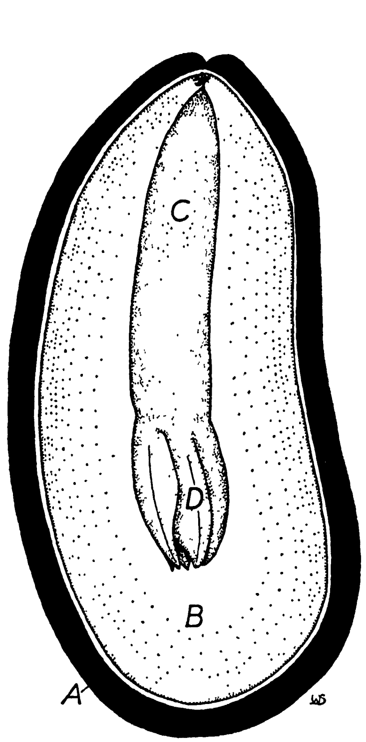


From Fuller, *The Plant World*

FIG. 107.—An opened bean seed with one of the two cotyledons removed, revealing the *body* of the embryo, which consists of the *hypocotyl* (C) and the *epicotyl* (D). A, seed coat; B, cotyledon.

The point of attachment between the cotyledons and the *body* of the embryo (Fig. 107) subdivides the body into two parts: (1) the *hypocotyl* (literally, below the cotyledons), a tapering, slightly curved, rodlike part; and (2) the *epicotyl* (literally, above the cotyledons), a small upper part, which must be dissected with needles before its structure can be seen. Such a

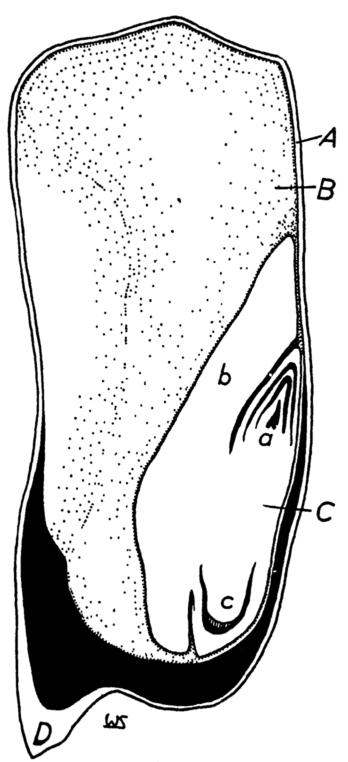
dissection reveals that the epicotyl of the bean consists of a pair of delicately folded *embryonic foliage leaves*, the *plumules*, and a small central conical mass, the *embryonic bud*.



From Fuller, *The Plant World*

FIG. 108.—Longitudinal section of pine seed

A. Seed coat
B. Endosperm
C. Hypocotyl
D. Cotyledons



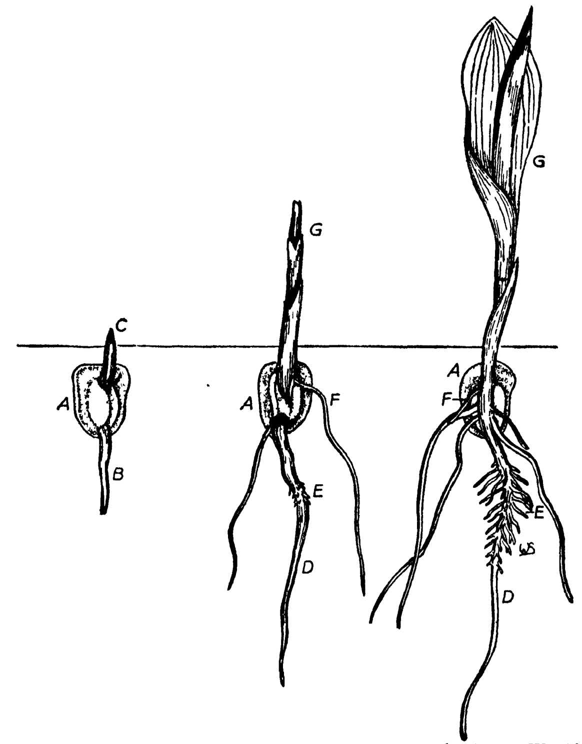
From Fuller, *The Plant World*

FIG. 109.—Longitudinal section of a corn grain, a one-seeded fruit

A. Grain coat (pericarp and seed coat)
B. Endosperm
C. Embryo: a. epicotyl, b. cotyledon, c. hypocotyl
D. Grain stalk

Seed structure varies widely among different Spermatophytes, but three main types are generally recognized. In Gymnosperm seeds, the embryo possesses 6-10 cotyledons, which are needle-like in form and not very conspicuously swollen (Fig. 108).

And among Angiosperm (p. 242) seeds the embryo possesses either *two* cotyledons, as in the Dicotyledoneae; or only one cotyledon, as in the Monocotyledoneae (see Fig. 109).



From Fuller, *The Plant World*

FIG. 110.—Germination of corn grain

A. Grain
B. Hypocotyl
C. Epicotyl (covered by epicotyl sheath)
D. Primary root
E. Secondary roots
F. Adventitious roots
G. Shoot

The developmental fate of the embryonic parts likewise varies in different seeds. In the pea and corn, for example, the cotyledons remain below ground as the seedling develops, and thus the hypocotyl gives rise only to the root system, and the epicotyl produces all of the stem and leaf systems (Figs. 110 and 111). But in the bean and pine, the cotyledons are lifted above ground, and thus the hypocotyl gives rise to part of the stem,

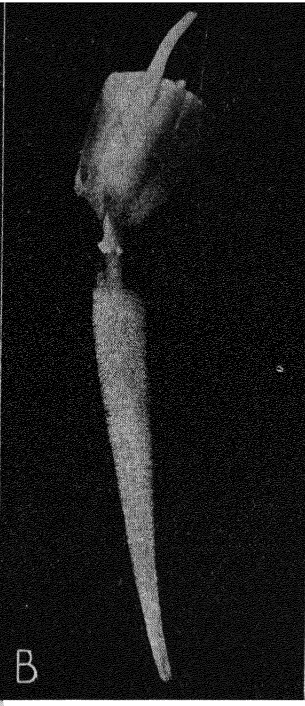


Photo by O. T. Bonnett

FIG. 111.—Germinating grains.

A. Corn grain in early stage of germination. The primary root has penetrated the sheath and is emerging from the grain.

B. A later stage in the germination of a corn grain. The primary root has numerous root hairs, and the plump epicotyl has emerged. Adventitious roots are seen below the epicotyl.

C. A germinating wheat grain, showing the primary root with root hairs, the short blunt epicotyl, and several young side roots.

as well as to the root system (Fig. 106). In the pines and many other plants, the cotyledons develop chlorophyl; and in some cases the cotyledons persist as foliage leaves, after their reserves of organic matter have been exhausted.



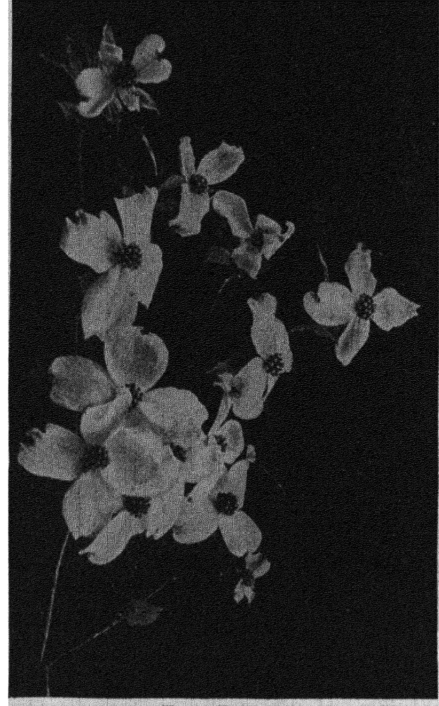
From Fuller, *The Plant World.* Photo by C. F. Hottes

FIG. 112.—Bees entering snapdragon flowers, a feat possible only for large strong insects. The stigma of the snapdragon is so placed that it inevitably receives pollen from the hairy back of the bee, if the bee has previously visited another snapdragon.

Variations of Floral Structure. Pollination has been a main factor in determining the evolution of the floral structure. Some species practice self-pollination, in which case the floral envelopes (calyx and corolla) tend to remain closed when the pollen is liberated. But a great majority of species depend upon cross-pollination, and the main *vectors* of pollen from plant to plant are: (1) the wind, and (2) animals, chiefly insects.

In general, bright and conspicuous petals (or sepals), distinct

fragrances, and *nectar glands* represent adaptations which have arisen from a long evolutionary association between the Angiosperms and insects. As is well known, many insects fly from flower to flower, seeking food (nectar and pollen), and incidentally carrying the pollen. In some cases, one finds a very specific



From Fuller, *The Plant World.*
Photo by C. F. Hottes

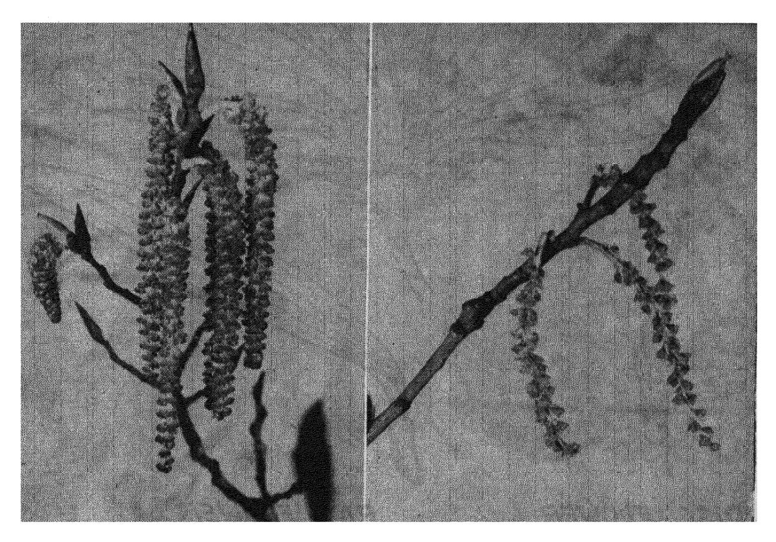
FIG. 113.—Inflorescences of dogwood (Cornus florida). Each inflorescence consists of several very small flowers subtended by 4 large, white bracts.

relation between the form of the flower and that of the insect vector (Fig. 112).

Some plants possess modified leaves near the flower proper, and sometimes these *bracts* are bright and showy, usurping the insect-attracting function of the smaller true petals (e.g., the poinsettia and dogwood, Fig. 113).

In wind-pollinated flowers (e.g., the cottonwood, Fig. 114),

petals and sepals are either lacking or inconspicuous, and usually the pistils and stamens occur in separate flowers. Such *incomplete* flowers are held aloft on the outermost branches of the plant, where there is a maximum exposure to the wind; and usually wind-pollinated flowers appear early in the spring, before the leaves come out to interfere with the transfer of the pollen—



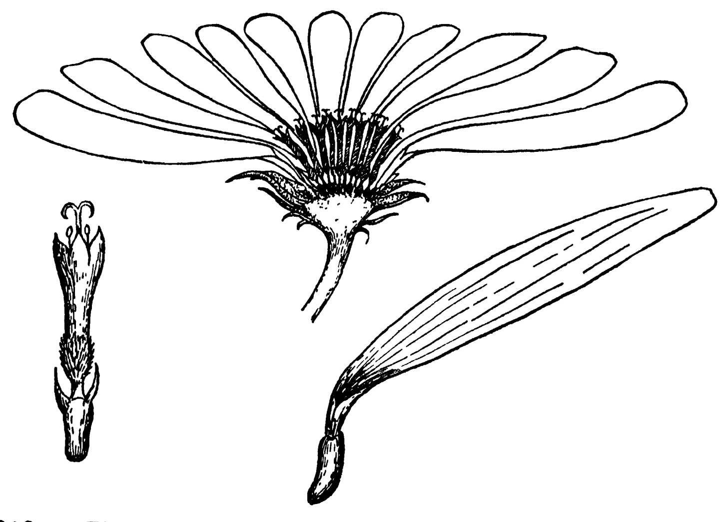
From Fuller, *The Plant World*

FIG. 114.—Staminate (left) and pistillate (right) inflorescences of cottonwood, Populus deltoides. Cottonwoods are wind-pollinated.

which is produced in very large amounts. Most of our common deciduous trees (maples, elms, willows, oaks, etc.) possess wind-pollinated flowers.

Frequently a multiple cluster of flowers is borne on one stalk (*peduncle*), which may or may not be branched (Figs. 113 and 114). Such floral clusters technically are called *inflorescences*, of which there is a wide variety of types. One very common type of inflorescence is possessed by the dandelions, daisies, sunflowers, dahlias and the other members of a large family, the Compositae. The large "sunflower," for example, is an inflorescence composed of a multitude of very small individual flowers, which are of two sorts (Fig. 115). The sterile *ray flowers*, which

lack both pistils and stamens, are arranged radially around the outer margin of the circular *head*. These ray flowers account for most of the showiness and color of the "sunflower." But the production of seeds is left entirely to the functional *disc flowers*, which are massed compactly in the central region of the head.



From Hylander and Stanley, *Plants and Man*, by permission of The Blakiston Company

FIG. 115.—Diagram showing the individual flowers of the inflorescence of the sunflower.

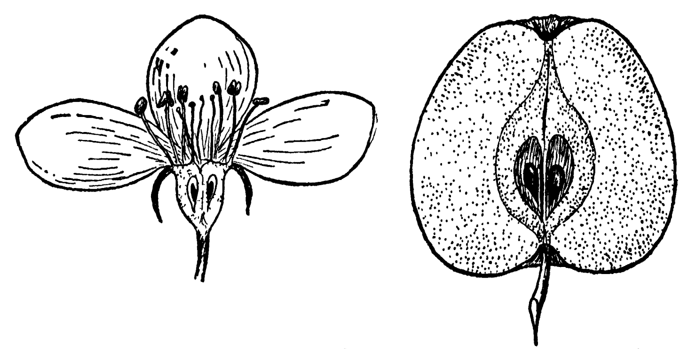
Variations of Fruit Structure. *The enlarged ripened ovule chamber, together with its content of seeds, is a fruit*, although in some cases (accessory fruits) other parts originally present in the flower may be incorporated in the fruit. For example, the apple (Fig. 116) is an accessory fruit of the *pome* type. In pomes, the receptacle of the flower surrounds the ovule chamber and gives rise to the skin and fleshy parts of the pome; and only the "core" of the apple comes from the ovule chamber.

Fruits, like flowers, occur in almost endless variety; and frequently fruit structures are important in relation to the dispersal of the seeds—by the wind, animals, or other agencies.

This relation may be seen in the following classification, which includes many of the most common types of fruit.

A. Dry Fruits. 1. *Winged fruits* or keys—as in maples, elms and ashes (Fig. 117). The wings are outgrowths of the *pericarp* (wall of the ovule chamber), which foster seed-dispersal by wind.

2. *Plumed fruits*, as in dandelions, sycamores, and milkweeds (Fig. 117). The plumes are also pericarpal outgrowths which facilitate wind dispersal.



From Hylander and Stanley, *Plants and Man*, by permission of The Blakiston Company

FIG. 116.—In pome fruits, such as the apple, the bulk of the fleshy part is derived from the receptacle of the flower.

3. *Barbed fruits*, as in the burdock (Fig. 117) and wild carrot. These fruits are dispersed as "hitch-hikers" on the fur or other skin covering of animals.

4. *Legumes*, as in peas and beans. The capsule of this pod-like type of fruit is derived from a single ovule chamber. When ripe, the pod splits open along both seamlike margins, discharging the seeds.

5. *Grains*, as in corn and wheat. Only the very thin outer cover, which is closely adherent to the true seed coat of these single-seeded fruits, is derived from the pericarp (Fig. 109).

6. *Nuts*, such as hazel nuts and acorns. In these single-seeded fruits, the thick hard outer shell is derived from the pericarp.

B. Fleshy Fruits. 1. *Berries,* such as the grape and tomato (Fig. 118). The "skin" and all the flesh of the berry is derived from the wall of the ovule chamber, which may be monocarpellate (grape) or polycarpellate (tomato) in origin. Many berries are eaten by animals, and a dispersal of the species may result when the undigested seeds are voided in another locality.

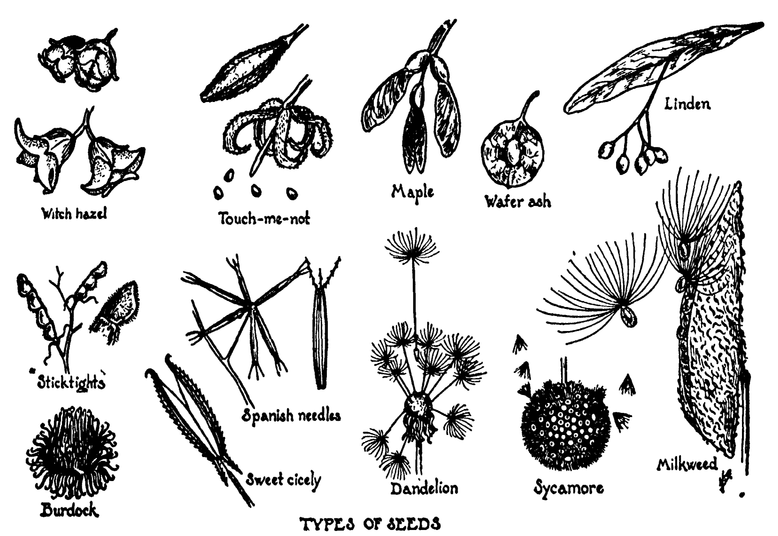


FIG. 117.—Types of seed- and fruit-dispersal mechanisms.

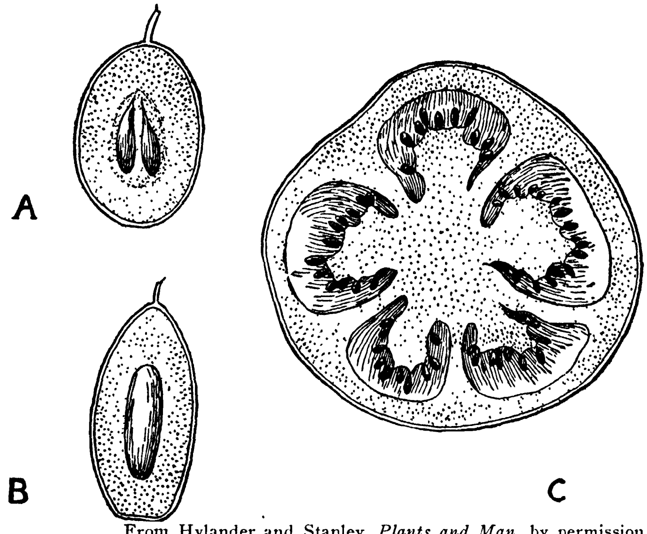
2. *Drupes,* such as peaches and plums. Not only the skin and flesh of these one-seeded or two-seeded fruits but also the stony coat directly surrounding the seed proper are derived from the pericarp. The seeds of such fruits are also distributed by animals which eat them.

Fruits are also classified as to the number of individual pistils which are originally represented in the flower. Accordingly:

A. A *simple fruit* is one that has developed from a single pistil, and all the fruits previously mentioned (except the burdock and maple) are simple fruits.

B. An *aggregate fruit* is a cluster of ripened ovule chambers, the pistils of which were all borne in the same flower, e.g., raspberries and blackberries.

C. A *multiple fruit* is a cluster of ripened ovule chambers, the pistils of which were borne in separate flowers, all having a common receptacle, e.g., the pineapple.



From Hylander and Stanley, *Plants and Man*, by permission of The Blakiston Company

FIG. 118.—Some common berries: A, grape; B, date; C, tomato.

Growth and Development in Plants. In general, the development of plant structures is much simpler than in animals. Most parts of the plant are essentially solid masses of cells, in contrast to the hollow or tubular nature of many animal organs. Animal development (see Chap. 14) involves a complex series of foldings, invaginations and cell migrations; but plant development occurs mainly at localized *growing points,* where the cells *multiply, grow,* and *differentiate,* forming the *tissues* of the adult organs.

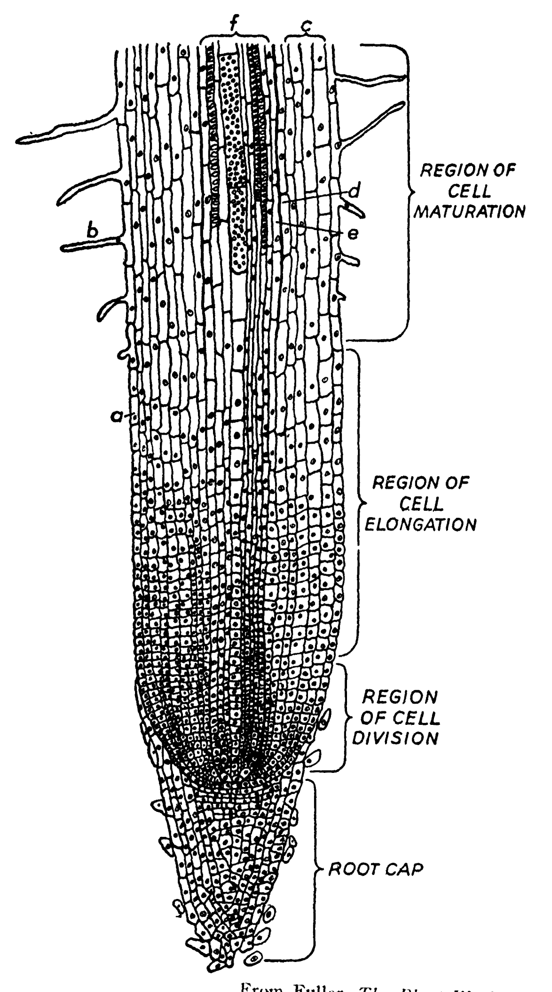
In thalloid plant bodies, the growing points are mainly localized at the apex of each filament, or lobe. At this point one usually finds a single large cell, the *apical cell,* which divides

continually, producing all the cells of the thallus. The apical cell remains more or less permanently in an undifferentiated condition, and retains an unlimited capacity for multiplication and differentiation. But most of the other cells become differentiated sooner or later, forming the specialized tissues in the different parts of the thallus.

Among higher plants, which possess roots, stems and leaves, cell division is largely restricted to growing points, which are localized masses of embryonic (*meristem*) tissue. The meristem cells remain in an undifferentiated state indefinitely, and retain their capacity for unlimited multiplication and differentiation. In the *root*, the growing point is located near the tip of each branch (Fig. 119); and in the stem, there is a growing point at the apex of each bud. However, many stems (Gymnosperms and dicotyledenous Angiosperms) possess a thin layer of meristem, the *cambium*, which encircles the trunk and its branches, underneath the bark. The cambium provides for increases in the *girth* of the stem. Also in most roots (Fig. 119) a layer of meristem, the pericycle, remains behind the growing point, providing for the origin of secondary offshoots from the primary root.

The nature of growth and development in plants is well illustrated by the case of a rootlet (Fig. 119). Virtually all new cells, both below and above the growing point, are formed by the multiplication of the meristem cells of the growing point. Below the growing point, the new cells become differentiated into the cells of the *root cap*. The root cap never becomes very large, however, because the cells keep scuffing off as the root pushes down into the soil (Fig. 119). Above the growing point, the cells increase in size (particularly in length), and become differentiated into the several kinds of specialized tissues which make up the *body* of the root. Such mature differentiated cells develop thick woody walls and become incapable of further growth and division.

In plants, growth tends to be *localized* and potentially *unlimited;* while in animals, growth occurs throughout the body and is more limited in scope. Most animals stop growing when



From Fuller, *The Plant World*

FIG. 119.—Longitudinal section of a young root of barley.

a. epidermis
b. root hair
c. cortex
d. endodermis
e. pericycle
f. differentiating conducting tissues

they achieve a certain size and form; but the size and form of a plant are limited mainly by external conditions.

Embryonic Development in a Dicotyledonous Seed Plant. After fertilization, the zygote begins development by a series of cell divisions. These first few divisions are all in one plane, producing a filament of cells, the *suspensor*, which pushes

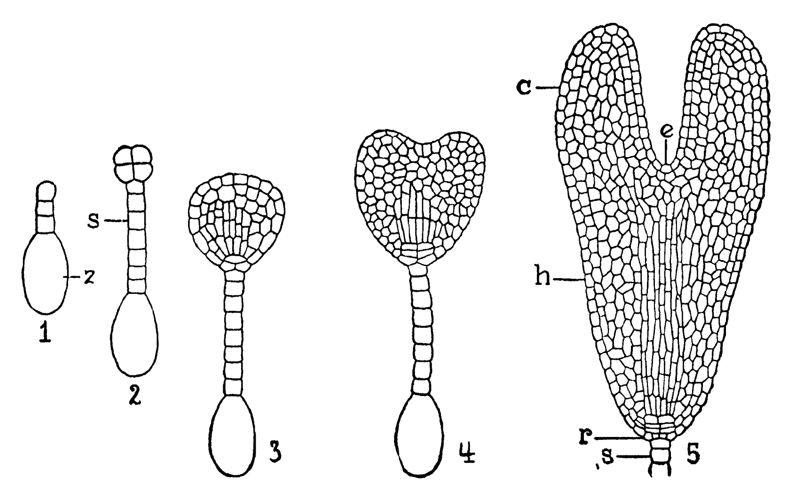
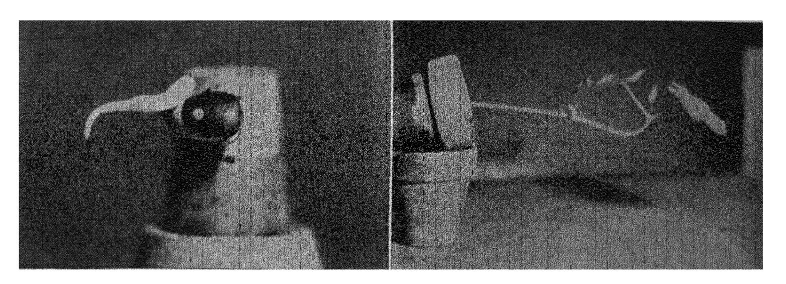


FIG. 120.—Development of a dicotyledonous embryo. z, original zygote cell; s, suspensor; c, cotyledon; h, hypocotyl; e, epicotyl; r, radicle. Later stages are shown in Fig. 105, O and P.

along the main axis toward the center of the endosperm tissue (Fig. 105, M). The end cell of the filament begins to divide in other planes, forming a rounded mass of cells (Fig. 120). The whole embryo is formed from this rounded mass of cells, and the suspensor degenerates before the seed is ripe. Growth and cell division now become most rapid at the sides of the embryo, near the free end. This results in two large outgrowths, which become the *cotyledons*. Meanwhile one end of the embryo elongates to form the *hypocotyl*, and the *epicotyl* begins to appear in the notch between the extended cotyledons. In some plants the embryo stops growing before it occupies the whole seed—in which case an endosperm persists around the embryo (Fig. 109). But in the bean (Fig. 107) and most other Dicotyle-

doneae, the cotyledons continue to grow, absorbing all the substance of the endosperm before the seed is ripe. In any event, the integuments of the ovule finally become thicker and tougher, forming the seed coats.

Germination. When a seed is ripe, development stops temporarily. Under natural conditions most seeds remain in the dormant state throughout the winter or dry season; and some seeds cannot be forced to germinate without the intervention of



From Fuller, *The Plant World*

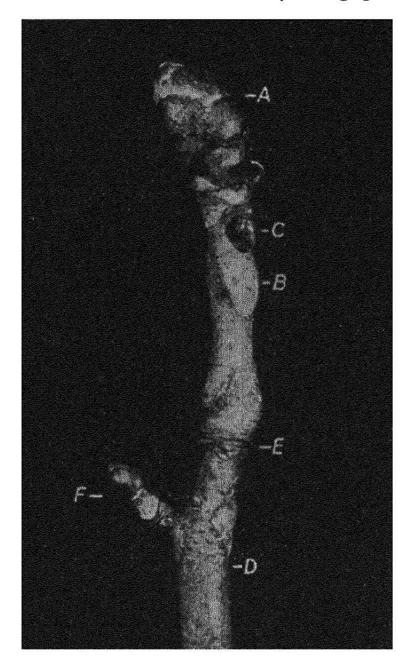
A B

FIG. 121.—A. Positive geotropism in primary root of bean. B. Negative geotropism in young stem of bean plant.

a definite resting period. At the proper time, with the advent of warmth and moisture, the seed absorbs water, swells powerfully to burst the seed coats, and now the embryo resumes development.

The hypocotyl elongates rapidly, forming the primary root, which soon develops a zone of root-hairs just above the tip (Fig. 106). The primary root is positively geotropic and grows downward, regardless of the position in which the seed may happen to lie (Fig. 121, A). At the same time, or shortly later, the epicotyl, being negatively geotropic (Fig. 121, B), begins to grow upward, forming the primary stem and the leaves. During these early stages of growth the young sporophyte draws upon the reserve organic nutrients stored in the cotyledons and endosperm (if present). This organic material is partly oxidized for energy and partly transformed into essential organic components in the growing cells. Despite the fact that the total

amount of organic material is decreasing during this period, the actual size of the young plant increases greatly, due to the fact that a large amount of water is absorbed as the new protoplasm is formed. In some plants the cotyledons, after giving up their organic reserves, develop into ordinary foliage leaves, although more often the cotyledons shrivel and finally drop off. In either case, chlorophyl forms in the young leaves (and stem) shortly after they reach the light; and when the organic reserves originally present in the seed are exhausted, the young plant becomes entirely self-supporting.



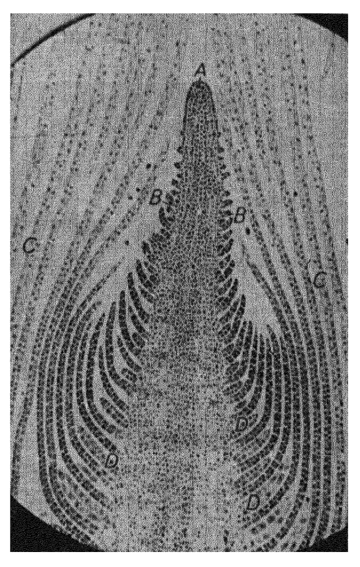
From Fuller, *The Plant World*

FIG. 122.—Portion of horse-chestnut twig.

A. Terminal bud in early stage of opening.
B. Leaf scar, where formerly a leaf was fastened to the stem.
C. Axillary bud, which originates in the leaf axils.
D. Lenticels.
E. Bud scale scars, from shedding of the scales of the former terminal bud.
F. Branch twig with terminal bud at apex.

Further Stages of Development. New branches and leaves originate from *buds*, which are generally situated at the apex and on the sides of the stem and its branches. The *terminal buds* provide for an elongation of the stem or branch; and the *lateral buds* give rise to more branches (Fig. 122). The lateral buds are also called *axillary buds*, because each one lies in a leaf *axil*—i.e., in the acute angle between the stem and the stalk, or *petiole*, of a leaf (Fig. 122). The immature bud is merely a conical mass of meristem tissue; but in mature buds (Fig. 123), partially developed leaves are present. The

young leaves first appear as lateral outgrowths from the young bud; but gradually the young leaves overgrow and envelop the growing point of the bud (Fig. 123). Some buds remain in a dormant stage, without further development, for some time—as is true of the *winter buds* of trees. Such resting buds are usually of the *protected* type; i.e., they possess an outer covering of horny modified leaves, called *scales*, which envelop the delicate embryonic leaves and the growing point of the bud (Fig. 122).



Copyright General Biological Supply House, Chicago

FIG. 123.—Bud of Elodea, a naked bud. The growing point (A) lies at the top; and along the sides, secondary buds (B and D) alternate with the leaves (C).

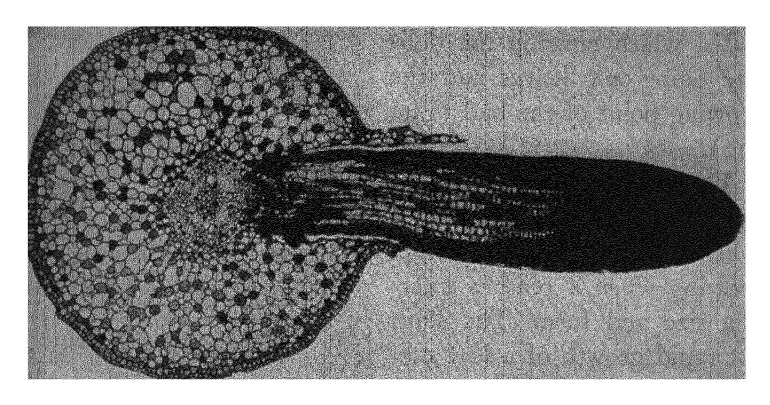
The growth of a leaf, unlike that of most stems and roots, is *limited*—i.e., the leaf stops growing when it reaches a certain size and form. The short but rapid growth of a leaf subsides first in the basal portion, and only later does the apex of the leaf reach its maximum size.

In perennial plants, the *primary stem* may continue to elongate year after year as the terminal bud goes through its alternate periods of rest and growth. *Branches* of the stem originate from the axillary buds, but many axillary buds do not develop unless the terminal bud is cut off or otherwise destroyed. Accordingly, the general shape of many plants can be modified quite drastically by pruning.

The growth of roots differs somewhat from that of stems. Roots never give rise to buds or leaves, and the growing point is generally covered by a root-cap. Secondary branches of the root originate at various levels above the growing point (Fig. 124), from the pericycle, which lies near the core of the root. Accordingly, each new secondary root must break its way out

through the cortical tissues of the old root. Some plants can form *adventitious roots* from any part of the stem, and in rare cases, even from a leaf.

Flowers develop at the ends of special stems, which are unable to grow beyond a fixed limit. Initially a *floral bud* looks much like a foliage bud, but later the terminal leaves modify their development and become the sepals, petals, stamens, and car-



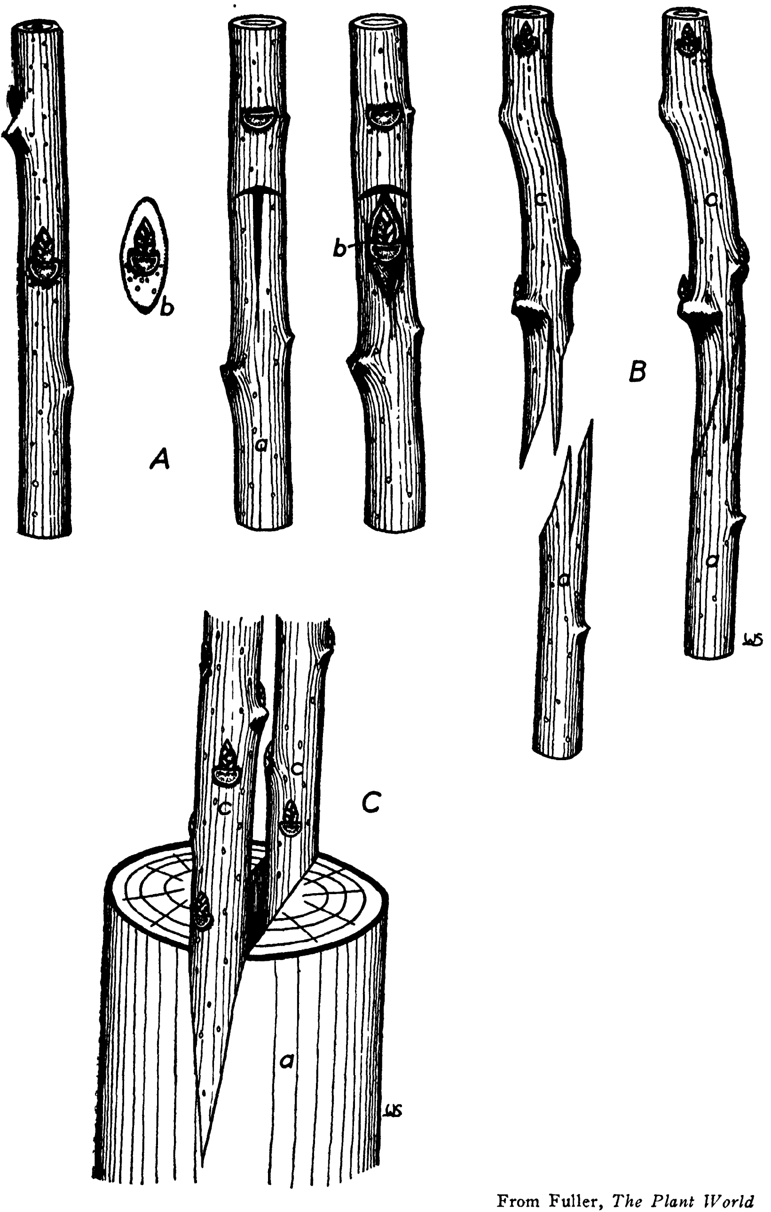
Courtesy of Triarch Botanical Supplies

FIG. 124.—Section of a primary root—showing the origin of a side branch, or secondary root.

pels. In the case of *mixed buds*, both foliage and floral branches originate from the same bud.

Vegetative Methods of Reproduction. Many plants exhibit a variety of reproductive processes which do not involve the production of either gametes or spores. In these *vegetative* methods of reproduction, the new plant usually arises from some multicellular part of the parent which contains some meristem tissue.

Many Bryophytes and Pteridophytes, and a few Spermatophytes, form modified buds, called *bulbils*, or *gemmae*, which develop into new plants after they become detached from the parent. Other plants—such as the strawberry—send out *runners*, or prostrate stems, producing offspring from the buds of the runners. New plants may also arise from the buds, or *eyes*, of swollen underground stems, called *tubers* (e.g., the potato).



From Fuller, *The Plant World*

FIG. 125.—Grafting methods:

A. Budding
B. Whip-grafting
C. Cleft grafting

a. stock
b. "bud wood"
c. scion

Bulbs, which are swollen underground buds, produce new bulbs in the axils of the scalelike leaves; and each new bulb can give rise to a separate plant.

In many plants, a slip, or *cutting*—i.e., a piece cut from a stem—may send out adventitious roots and develop into a new plant; and in a few cases, a leaf, or even a portion of a leaf, may do the same thing. *Grafting*, on the other hand, involves the combining of portions of two plants; and grafting has become a valuable and widely practiced technique among fruit growers (Fig. 125). All vegetative methods of propagation provide a practical advantage to nurserymen. Vegetative reproduction never involves the processes of meiosis and fertilization, and therefore the new plant always receives exactly the same set of chromosomes and hereditary characters as was possessed by the parent plant. Accordingly, the nurseryman is sure that the desirable qualities of a certain fruit tree, or potato, or other commercially valuable species are perpetuated in the new plants. A number of Spermatophytes, including the banana, have lost their capacity for forming functional seeds, and are propagated solely by vegetative methods.

TEST QUESTIONS

1. Make labelled sketches showing the main features of: (a) the sporophyte; and (b) the gametophyte, of a fern.
2. What is the basis for recognizing the leafy fern plant as a sporophyte, and the prothallium as a gametophyte?
3. Specify the five phyla of the plant kingdom and explain how the representatives of each group are to be distinguished on the basis of their life cycles.
4. A. Make labelled sketches to show the main stages in the life cycles of: (a) Spirogyra and (b) the bread mold;
   B. Indicate the haploid and diploid stages and specify the points where meiosis and fertilization occur.
5. Identify each of the following structures and give their localization in either the moss, or the fern, or both: (a) sporangia, (b) sporocytes, (c) spores, (d) sorus, (e) antheridia, (f) arche-

gonia, (g) venter, (h) rhizoids, (i) fertilized egg, (j) foot, (k) protonema, (l) apical notch.

6. Describe the life cycle of Selaginella. Why is this cycle generally considered to represent a transition between the cycles of the Pteridophytes and Spermatophytes?
7. Identify and locate each of the following structures and wherever possible provide a synonym: (a) the pistil, (b) carpels, (c) the ovule, (d) the macrospore, (e) a stamen, (f) an anther, (g) a pollen grain, (h) the calyx, (i) the corolla, (j) the receptacle.
8. Make a labelled sketch to identify the female gametophyte of a seed plant. Where and when is this gametophyte to be found in a flower?
9. How does the female gametophyte of a seed plant either resemble or differ from the gametophytes of the fern and moss in regard to: (a) origin, (b) chromosome count of the component cells, (c) function, (d) mode of nutrition, (e) complexity of structure; (f) prospects of reaching maturity, (g) prospects of having the egg fertilized?
10. Carefully explain points (f) and (g) of the preceding question.
11. Differentiate between a seed and an ovule. What special features of seeds generally account for the success of the seed plants in spreading throughout the land areas of the earth?
12. Supply the missing parts of the following statements:
    a. all the cells of the embryo sporophyte, which occupies the center of a seed, are derived by mitosis from the —— ——;
    b. each seed, as a whole, originates from an ——; whereas the fruit, as a whole, originates from the ——.
13. Identify and locate: (a) cotyledons, (b) the hypocotyl, (c) the epicotyl, (d) the plumule, (e) the embryonic bud, and (f) the suspensor.
14. In the bean and pea respectively, what parts (if any) of the adult sporophyte originate from: (a) the hypocotyl, (b) the epicotyl, and (c) the cotyledons.
15. In general, how are the parts of the flower modified in relation to the methods of pollination?
16. Enumerate five kinds of *dry fruits* and two kinds of *fleshy fruits*, giving the distinguishing features and an example of each type.

17. What is *cambium* and why is it important? What kinds of stems lack cambium?
18. What is a seedling? Explain the general importance of cotyledons (and endosperm, if present).
19. Identify each of the following: (a) lateral or axillary buds; (b) pericycle; (c) adventitious roots; (d) a bulbil; (e) a runner; (f) a tuber; (g) a bulb; (h) a cutting.

FURTHER READINGS

1. *The Plant World*, by Harry J. Fuller; New York, 1941.
2. *Textbook of Botany*, by Transeau, Sampon and Tiffany; New York, 1940.

CHAPTER 12

NUTRITION OF MULTICELLULAR PLANTS

Holophytic nutrition became dominant in the plant kingdom during an early evolutionary period; and as *multicellular* species developed they gained greater efficiency by a division of labor among the cells. Thus gradually the specialized tissues and organs of the modern higher plants came into being.

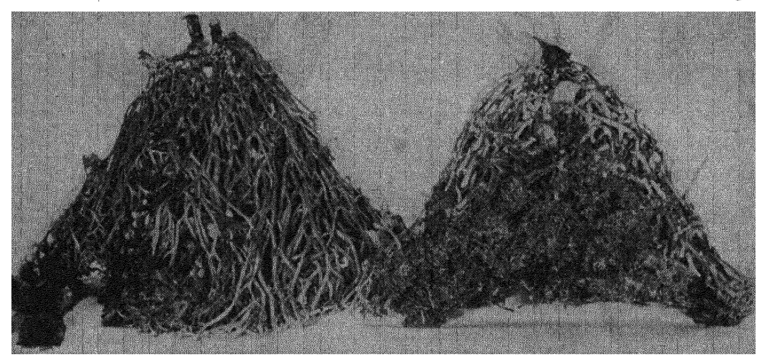
Multicellular Algae. All early primitive plants lived under water; and the aquatic environment puts little premium upon the development of specialized parts. Natural bodies of water contain adequate amounts of carbon dioxide, oxygen, and inorganic salts, so that every cell of a submerged plant can absorb these foods on an individual basis. Hence—as might be expected—the degree of differentiation among the cells of the green algae has not been very great.

Perhaps the commonest type of cell-differentiation among non-motile green algae is the modification of some of the cells to form organs of *attachment*. In some filamentous algae, a single cell at the basal end of the filament is specialized as a *rhizoid* (or holdfast) which attaches the filament to the soil or rock at the bottom of the water (Fig. 126). This specialized cell is modified in shape and lacks chlorophyl. The rhizoid cell is dependent on the other cells of the filament; and sugars produced by photosynthesis in the green cells are transferred to this colorless cell by osmosis through the intervening cell membranes.

Among the most highly differentiated of fresh-water algae is Nitella (Fig. 127). This relatively large green alga may measure almost a foot in length. Nitella exhibits a branching green

the nodes in a manner which is characteristic of the growth of higher plants.

Some larger marine algae (seaweeds) possess multicellular rhizoids, or "holdfasts," which are rootlike organs (Fig. 128). But rhizoids have a far simpler structure than true roots, and serve only for attachment. A chief function of a true root is to absorb water and dissolved substances; but in the algae this function is performed by all the cells individually. Many large



From Fuller, *The Plant World*. Photo by H. L. Andrews

FIG. 128.—Holdfasts of a seaweed (Macrocystis). California coast.

seaweeds also develop structures which *externally* resemble the true stems and leaves of higher plants, although *internally* these organs display only a small degree of cellular differentiation.

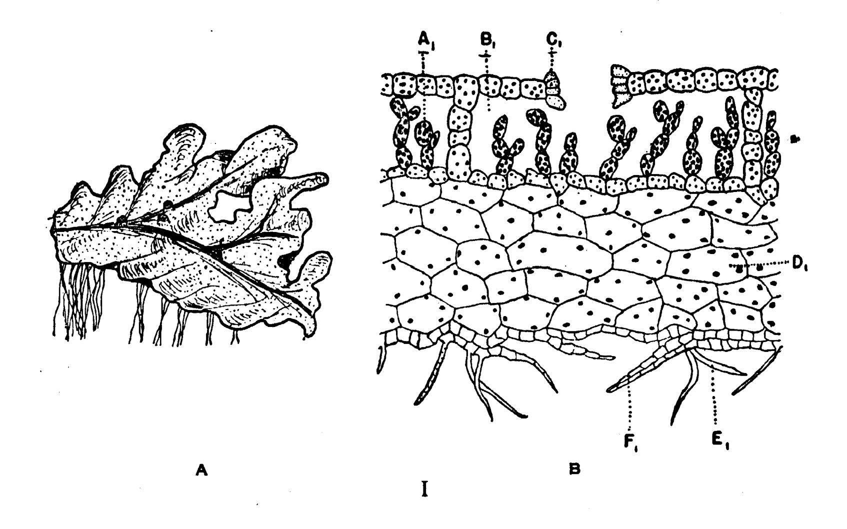
The Land Environment. To survive on land, plants must solve a serious dilemma. *In the soil*, water, salts, carbon dioxide and oxygen are available—but there is no light. And above the soil, i.e., *in the air*, light is available, but the water supply is inadequate, and inorganic salts are lacking. Therefore a truly successful land plant must possess parts which extend down into the soil, and parts which reach up into the air. Accordingly the conditions of the terrestrial habitat have determined the development of *roots*, *stems* and *leaves*, which are the main *nutritive organs* of all well-adapted land plants. Typically *roots* extend down into the soil to anchor the plant in an erect position and to *absorb* enough water and dissolved mate-

rials to meet the needs of the whole plant. The *leaves* are the specialized organs of photosynthesis, which pass on extra glucose to the rest of the plant; and the *stem* supports the leaves, and transmits substances up and down between the leaves and roots.

Nutrition of the Bryophytes. The simplest and most primitive of *terrestrial* plants are the Bryophytes (p. 230). This phylum consists of two groups: (1) the *liverworts* (class Hepaticae, Fig. 129); and (2) the mosses (class Musci, Fig. 97). None of the Bryophytes are very well adapted to land conditions—the liverworts even less so than the mosses. In all Bryophytes the main burden of nutrition falls upon the gametophyte generation—the sporophytes being relatively small and completely dependent. Consequently the nutritive processes of only the gametophytes will be discussed.

The Liverworts. The liverworts are small semi-terrestrial plants, unfamiliar to most people. The flat *thallus* body (Fig. 129, A), which seldom has an area of more than one or two square inches, grows in contact with the moist ground. Only the upper surface of the thallus is exposed to light; and the lower surface, which lies in contact with the ground, sends numerous colorless rhizoids downward into the soil. Usually many plants lie crowded closely together, completely covering the moist ground in a region which is frequently flooded by a neighboring spring, or by seepage from a hillside.

These primitive land plants manage to survive even in the absence of true roots, stems, and leaves. The thallus displays a fairly complex internal structure, with considerable specialization among the cells (Fig. 129, B). To protect the thallus from the strong light and heat of the sun, and to prevent the plant from losing more water than it can absorb through the underlying rhizoids, the thallus is covered by a layer of *epidermoid tissue,* which is especially well developed on the upper surface. The outer walls of the epidermoid cells are thickened and cutinized (waxy), to prevent an indiscriminate evaporation of water from the delicate internal tissues, as the sun beats down upon the plant. Also the upper surface is equipped with clearly de-



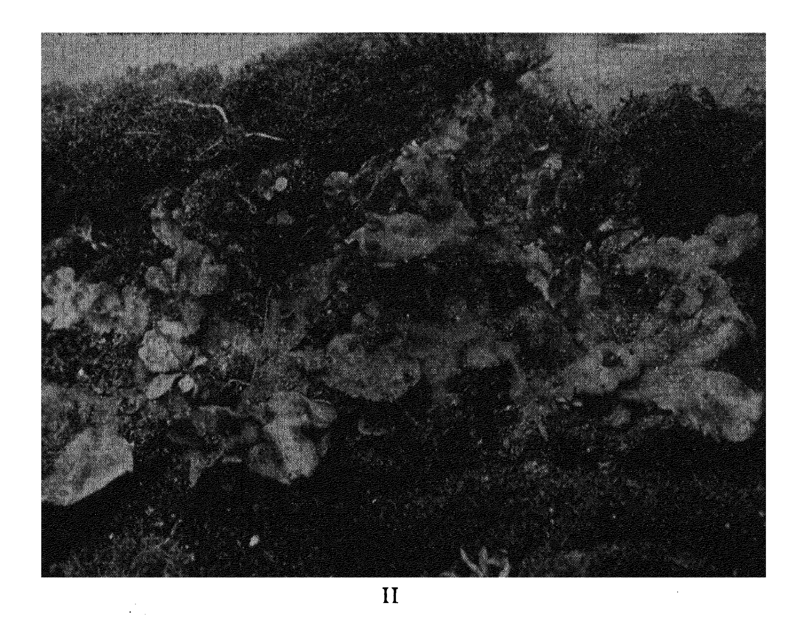


FIG. 129.—I. The thallus of a liverwort (Marchantia). A, whole thallus; B, vertical section through the thallus; A_1, chlorenchyma; B_1, gas space; C_1, pore cells; D_1, storage tissue; E_1, a rhizoid; F_1, a scale. II. A clump of liverworts (Marchantia polymorpha). The reproductive heads of the gametophytes are just beginning to show in a few of the specimens.

fined openings, the *pores,* each flanked by specialized *pore cells* (Fig. 129, B). The pore cells control the size of the numerous openings, tending to close them when the quantity of escaping water vapor becomes excessive. The pores lead into *air spaces,* inside the thallus, and these spaces permit carbon-dioxide to diffuse from the outside air to the delicate green cells, or *chlorenchyma,* which border the air spaces. The remaining thickness of the thallus is composed mainly of larger cells with fewer chloroplasts. These cells serve chiefly as a *storage tissue,* in which extra quantities of photosynthesized glucose are deposited in the form of starch grains. In addition to the storage tissue, the cells in the central parts of the thallus, especially along the "midribs" (Fig. 129, A), are unusually long, and display very active cyclosis. This *primitive vascular tissue* accelerates the *distribution* of substances from one part of the thallus to another.

The *rhizoids* (Fig. 129, B) are colorless elongate cells with delicate walls, adapted to the absorption of water and mineral salts. The rhizoids occur in clusters and each cluster is protected by one or more *scales,* which are multicellular extensions of the lower epidermoid layer. In dry weather, the scales tend to curl around the rhizoids, protecting them from desiccation.

Growth of the thallus is by the proliferation of *apical cells* at the end of each lobe. Frequently a growing point becomes divided into two masses of embryonic tissue, each of which generates a new lobe; and this method of growth accounts for the branching habit of the thallus.

The Mosses. The general form of the moss, with its small erect leaf-surrounded stem, was described previously (p. 235). Like the liverworts, typical mosses are only semi-terrestrial. They grow in densely crowded clumps, protecting each other from desiccation; and except for a few highly developed species, the mosses are restricted to damp and shady localities.

The internal (microscopic) structure of a moss plant is shown diagrammatically in Fig. 130. The *rhizoids,* which extend down into the soil from the lower end of the stem, are simple branched filaments of colorless elongate cells, often twisted into stout rootlike strands. Like the true roots of higher plants, the rhi-

zoids serve for both *absorption* and *attachment;* but structurally the rhizoids are much simpler than true roots (p. 263). In most

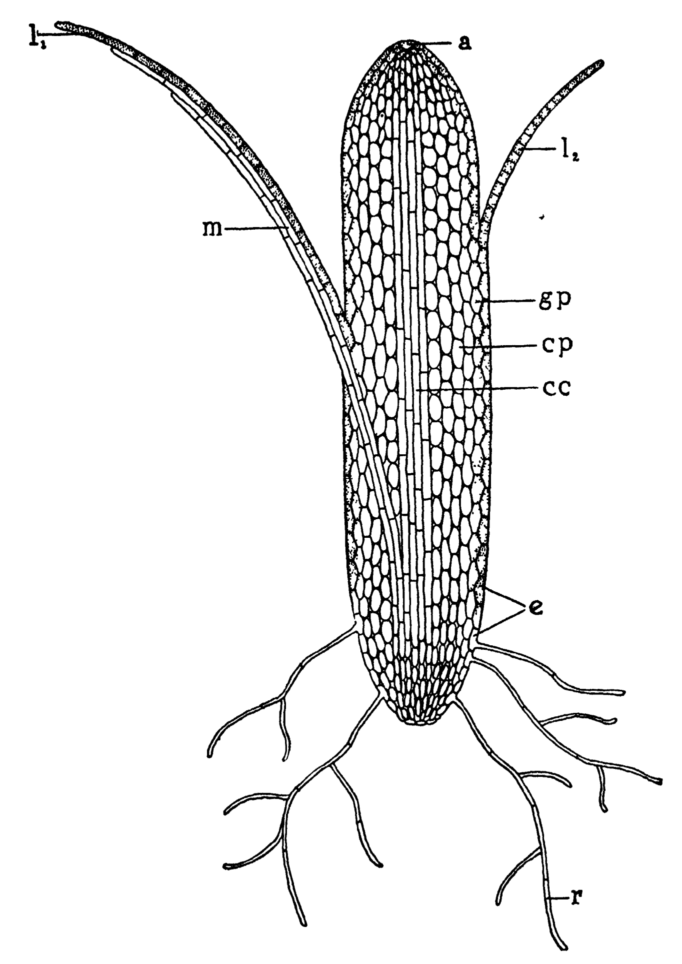


FIG. 130.—Diagram of longitudinal section of moss plant. a, apical cell; l, leaf cut through the midrib, m; l_2, leaf cut through blade; gp, green parenchyma; cp, colorless parenchyma; cc, central cylinder; e, "epidermis" (scarcely differentiated from the underlying parenchyma); r, rhizoid.

mosses, the blade of each *leaf* consists of a *single layer* of rather thick-walled cells, which contain numerous chloroplasts. During photosynthesis—and this is the special function of the leaf

as a whole—each individual cell absorbs carbon dioxide directly from the air. But water, which is needed simultaneously in photosynthesis, is obtained from the rhizoids, via the stem and *midrib* of the leaf. The *midrib*, or central axis of the leaf, is somewhat thicker than the blade, due to the presence of several strands of elongate cells placed end to end along the length of the leaf. This *primitive vascular tissue* serves not only to carry water and salts out into the leaf, but also to take glucose, and other organic substances, back from the leaf to the other parts of the plant.

The *stem* of a moss plant exhibits three fairly distinct concentric zones: (1) an outer zone made up of several layers of green cells; (2) an intermediate zone of larger more loosely packed colorless cells; and (3) an innermost core of elongate slender cells (Fig. 130). Some photosynthesis occurs in the green cells of the outer layers. However, these cells have thick cutinized walls, and their chief function is to waterproof the external surface of the stem—since very few mosses possess a distinct epidermal covering. The intermediate zone of thin-walled cells is for the storage of reserve organic substances, chiefly starch, although their loose arrangement provides air spaces to facilitate the *respiration* of the stem as a whole. The primitive vascular tissue in the central core of the moss stem serves for the *distribution* of inorganic materials *upward*, and of organic products *downward*, through the plant. In a few mosses the end walls of the vascular cells—where they make contact with each other end to end—are perforated, so that protoplasmic continuity exists from cell to cell, as in the *sieve tubes* of higher plants (p. 285). *Growth* occurs by the multiplication of an apical cell at the top of each stem. The leaves, and in a few species branches, originate as buds from this growing point.

Organs and Tissues of the Bryophytes. In summary, the specialized organs and tissues of higher land plants are foreshadowed only feebly in the Bryophytes. Without *true roots*, capable of absorbing water on a quantity basis, the Bryophytes have not developed an extensive leaf surface, since such a surface would expose the plant to an excessive loss of water. More-

over, many Bryophytes, i.e., the liverworts, have not developed even a primitive stem system.

Likewise the *tissues* of Bryophytes are only partially differentiated. The *epidermoid* and *storage tissue* cells possess chloroplasts and continue to carry on photosynthesis as a secondary function; and the vascular tissue of Bryophytes is of a very primitive type, which does not approach the efficiency of the *true vascular tissues* (p. 285) of the Pteridophytes and Spermatophytes.

Transitional Developments: Ascendance of the Sporophyte Generation. Among the Bryophytes the *gametophyte generation* displays a limited fitness to cope with the land environment; and little evolutionary progress has been made by Bryophytes in recent geological times. Meanwhile the *sporophyte generation* of the higher plants evolved an efficient system of specialized organs and tissues; and the modern Pteridophytes and Spermatophytes are well adapted to land conditions. In this evolution, however, the *gametophyte generation* of the higher plants has retrogressed and become relatively insignificant, especially from a nutritive point of view. Although the gametophyte (prothallium) of the fern is an independent plant, its nutritive processes are not any more complex than those of the liverwort; and the gametophytes of the *seed plant* are microscopic bodies, which are nourished entirely by the tissues of the sturdy land-adapted sporophytes (p. 246). In the following sections, therefore, the nutrition of the gametophyte generations will not be considered; and only the nutrition of the sporophytes of the higher plants will be discussed.

Nutritive Organs and Tissues of the Vascular Plants. Collectively the Pteridophytes and the Spermatophytes are called the *vascular plants*. All these plants have developed *true vascular tissues*, which are essential to any large species living on dry land. The vascular plants are all quite similar as to their nutritive organs and functions. Accordingly most of the following discussion will deal with the Angiosperms, which include a large majority of common plants.

Tissues of the Vascular Plants. The following tissues, classified according to function, are present in all vascular plants:

1. *Meristem tissue* (also called *embryonic parenchyma*). Meristem tissue has an unlimited capacity for *multiplication* and *differentiation;* and all the specialized tissues (listed below) are derived from the meristem of the growing points of the plant. Typically the meristem consists of small thin-walled cells, which possess chloroplasts, and which divide continuously, forming more meristem.

2. *Epidermal tissues.* Epidermal tissues provide a suitable covering for the various surfaces of the plant. Typical epidermal cells fit closely together with a minimum of intercellular material or space—forming a layer, which is only one cell deep. Epidermal cells vary in form in the different parts of the plant. In the leaf (Fig. 131), where the epidermis protects the internal tissues from losing too much water, the outer walls of the cells are thick and *cutinized.* Leaf epidermis is also unusually transparent, which allows light to pass through to the green tissue inside the leaf. Even in the leaf the epidermal cells do not possess chloroplasts. In the root, where the epidermis has an absorptive function, the cell walls are relatively delicate; and in the zone where absorption is most active, the epidermal cells of the root possess slender outgrowths, the *root hairs* (Fig. 15).

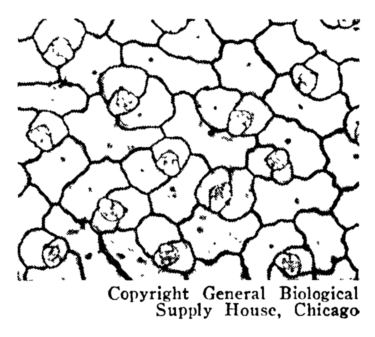


FIG. 131.—Magnified surface view of a Sedum leaf. Each stoma is flanked by a pair of small sausage-shaped *guard cells,* which fit in amongst the large irregular *epidermal cells.*

3. *Green parenchyma* or *chlorenchyma.* Parenchyma tissues are not highly specialized, i.e., the cells resemble meristem cells in greater or lesser degree. Green parenchyma possesses chloroplasts (Fig. 141), and photosynthesis is the main function. Green parenchyma cells are usually thin-walled and loosely packed. This arrangement provides a continuous system of *intercellular spaces* and facilitates the exchange of gases during

photosynthesis and respiration. Green parenchyma is localized mainly in the leaves, although some chlorenchyma is usually present near the surface in younger stems.

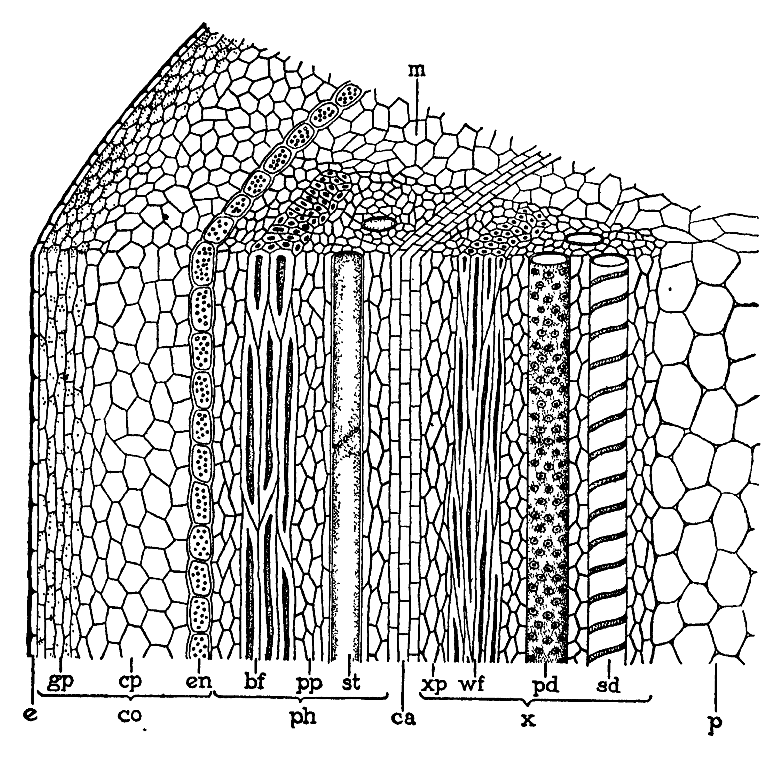


FIG. 132.—Tissues of the higher plants as shown in a diagrammatic section of the stem of an Angiosperm. e, epidermis; co, cortex: gp, green parenchyma; cp, colorless parenchyma; en, endodermis or "starch sheath," containing numerous starch grains. ph, phloem: bf, bast-fibers; pp, phloem parenchyma; st. sieve-tube; ca, cambium; x, xylem: xp, xylem parenchyma; wf, wood-fibers; pd, pitted duct; sd, spiral duct; p, pith; m, medullary ray.

4. *Storage parenchyma* or colorless parenchyma. This tissue resembles green parenchyma, except that the cells are generally larger and lack chloroplasts. The main function of colorless parenchyma is to store organic substances (chiefly starch); but the loose arrangement of the cells facilitates respiration in the stem and roots (Fig. 132, p).

5. *Strengthening tissues.* a. *Sclerenchyma:* This poorly defined tissue consists of elongate cells with very thick cell walls. In some mature sclerenchyma all the protoplasm may be replaced by the encroachment of the thick cell walls, which impart mechanical strength to the tissue. Sclerenchyma is present in many stems and roots, and in some leaves.

b. *Bast.* This modified type of sclerenchyma is found in the phloem (p. 292) of many stems (Fig. 132, bf). Initially each bast fiber is a living cell, which develops an elongate spindle-like shape and very thick walls. A mature bast fiber finally displays a small central hollow, which is devoid of any protoplasm (Fig 132, bf). The pointed ends of the spindle-shaped bast fibers tend to overlap each other, imparting great flexibility and strength to the tissue as a whole.

c. *Wood* likewise is a special type of sclerenchyma, which is found in the *xylem* (p. 292) of many stems (Fig. 132, wf). Wood fibers resemble bast fibers in origin and form. However, in wood the cell walls are denser, and this imparts a "harder" quality to the tissue.

6. *Vascular tissues.* a. *Sieve tubes* are tubular units found in the *phloem* of stems (Fig. 132, st), roots and leaves. Each sieve tube represents a column of elongate cylindrical cells, placed end to end. At maturity the end walls of these cells become perforated, forming the *sieve plates,* which give protoplasmic continuity between the successively placed cells in the column (Fig. 132, st). The protoplasm of the sieve tubes displays an active continuous *cyclosis,* which accelerates the distribution of substances lengthwise through the plant. The sieve tubes are concerned particularly with the transportation of glucose, and other organic products, *downward* in the plant.

b. *Ducts* are the tubular units localized in the *xylem* regions of roots, stems and leaves. The initial differentiation of a duct from embryonic parenchyma resembles that of a sieve tube; but later the side wall of the column of cells becomes much thicker; and gradually the end walls are *resorbed completely* (Fig. 132, pd and sd). Finally all the protoplasm disappears, leaving a free channel throughout the length of each duct. The ducts form

continuous channels from the roots up through the stem and into the leaves. Ducts serve to transport substances—particularly water and inorganic salts—*upward* through the plant. Several kinds of ducts are distinguishable. In *pitted* ducts, the side walls are pocked with numerous round depressions (Fig. 132, pd). These pits partially penetrate the cellulose and permit sub-

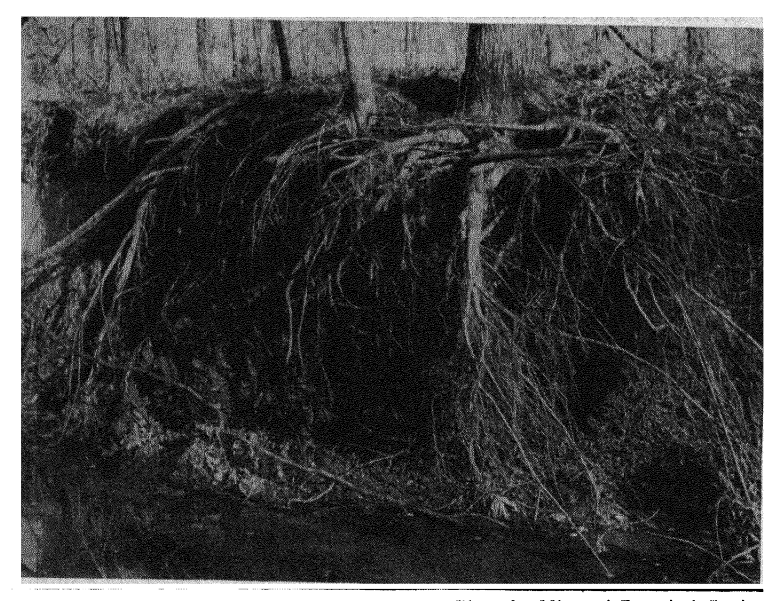


Photo by Missouri Botanical Garden

FIG. 133.—Roots of a white elm exposed by the encroachment of a stream.

stances to escape from the ducts, supplying the surrounding tissues at various levels of the plant. In *spiral* (Fig. 132, sd) and *annular* ducts, thickenings of the side walls can be seen, which give a "springlike" and a "ringlike" appearance to each respective type. In addition to the vascular function, ducts augment the mechanical strength of the various parts, especially in the stem.

The Root and Its Functions. The root system of a vascular plant has two main functions: (1) it *absorbs* water and salts for the plant as a whole; and (2) it *anchors* the plant in an upright position. Accordingly the roots of a plant ramify extensively

throughout the soil. In many trees the roots branch even more profusely than the stem (Fig. 133); and frequently the total root *surface* is greater than that of the stem with all its branches. However, the depth of roots seldom equals the height of the stem, although frequently the two systems have a corresponding lateral spread.

Not all parts of the root system are equally effective in the absorption of water and salts. In fact absorption is confined largely to the *root-hair* zone, which lies above the growing point in each of the many young branches, or *rootlets* (Fig. 134). This region of the root displays a highly organized structure, as may be seen in cross-section (Fig. 135). At the center lies the *vascular cylinder*, sheathed by a thick cortex. The vascular cylinder is composed chiefly of *ducts* and *sieve tubes*, surrounded by a single layer of growth tissue, the *pericycle*. The thickness of the cortex is due to the several layers of *colorless parenchyma*, which is covered externally by a thin epidermis, from which the root hairs are derived.

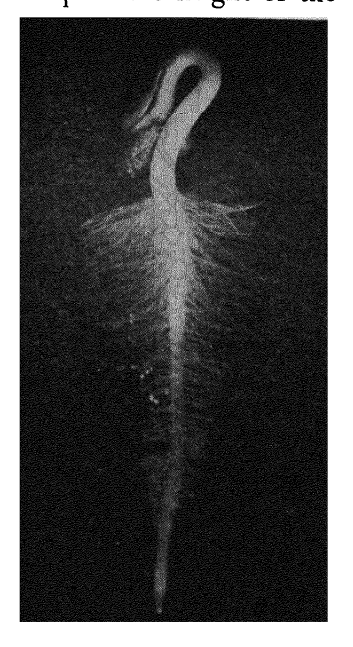
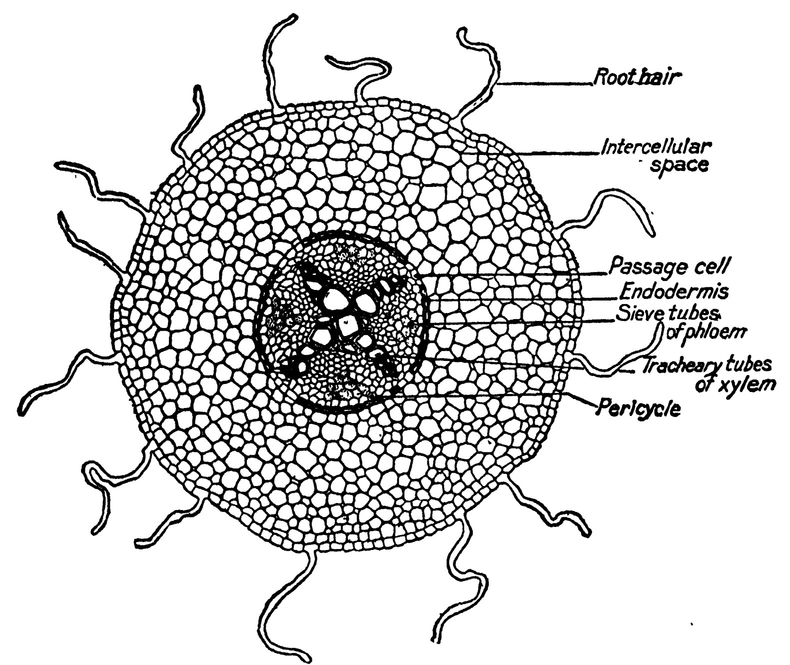


FIG. 134.—Root hairs as seen on a seedling of the garden cress grown in moist air (× 4).

Absorption by the root is determined mainly by osmosis. Water from the soil enters the root hairs and then passes across the cortex tissues, entering the *ducts* of the vascular cylinder (Fig. 136). The root hairs extend out from the epidermis and make contact with the film of water which wets the particles of moist soil (Fig. 137). Although confined to a short (1-2 cm.) zone near the root tip, each cluster of root hairs numbers sev-

eral thousand; and the total absorbing surface of the root system may amount to many square meters. The root hairs, being very delicate, dry out and die within a few minutes, if they are exposed to air. Consequently, if a plant is to be transplanted during the growing season, the soil around the roots must be



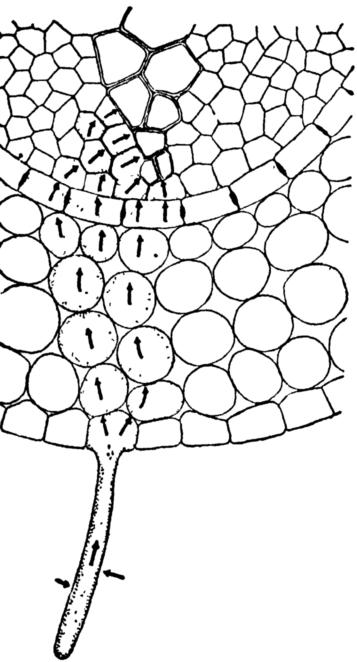
From MacDougall and Hegner, *Biology*, McGraw-Hill Book Co.

FIG. 135.—Diagrammatic cross-section of root in the root-hair zone. (After Weaver.)

disturbed as little as possible. This care avoids tearing the root hairs—which may be cemented to the soil particles—and protects them from being killed by drying. Without root-hairs a plant usually wilts and dies before new root hairs can be regenerated, because the root-hairs account for approximately 90 per cent of the osmotic surface of the root.

Soil water is a hypotonic solution of inorganic salts, which yields water to the root-hair cells; and as these epidermal cells take in water, they become hypotonic to the cells of the cortex.

Thus water continues to pass inward through the root tissues, toward the *ducts* in the vascular cylinder. The ducts contain the *sap* of the plant. This solution, because of its content of sugars and salts, is distinctly hypertonic, and tends to absorb water from the surrounding tissues. The water entering the sap generates a pressure in the ducts; and this *root pressure* forces the sap to flow upward through the plant. At the top of the plant, much water constantly escapes from the leaves (p. 295); and in the leaves new sugars are being synthesized and sent downward to the roots. These processes are necessary to maintain the hypertonicity of the root sap, and to foster a further absorption of water (see p. 298).



From Mavor, *General Biology*. By permission of The Macmillan Co.

FIG. 136.—Diagram showing the absorption of water from the soil through the root-hairs and other intervening tissues into the xylem in the vascular core of the root. (Redrawn after Smith, Overton, et al.)

The root also absorbs inorganic salts from the soil, although salts enter the sap much more slowly than water. Certain roots may be able to augment their salt absorption by energy-expending processes, but these processes are not well understood. Ordinarily, the sap absorbs inorganic salts in very small amounts, and consequently large volumes of sap must flow to the upper parts of the plant to supply the metabolic needs of the tissues (see later).

The Stem and Its Functions. The extensively branching *stem* system of the typical land plant has two primary functions: (1) it supports the leaves in a position which assures a maxi-

mum of photosynthesis, and (2) it conducts materials upwards and downwards between the leaves and the roots.

The vascular functions of the plant are performed mainly by the *ducts* and *sieve* tubes, which always occur in the form of organized strands, called *vascular bundles.* The vascular bundles of the stem extend downward into the root and upward into

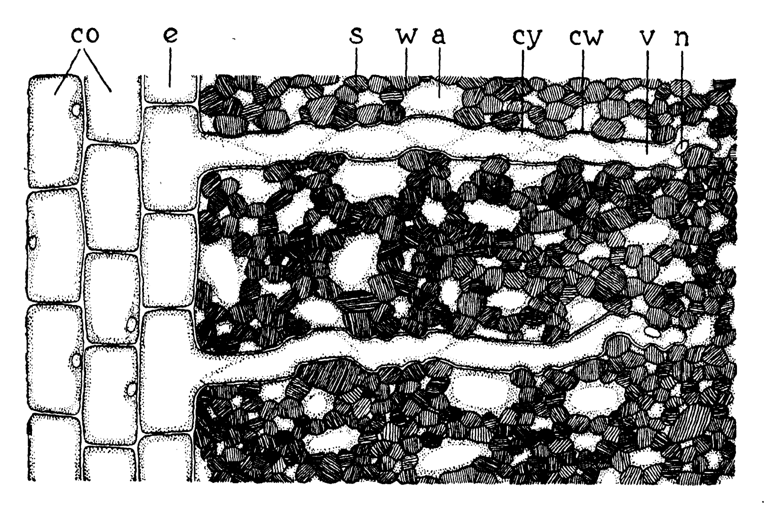


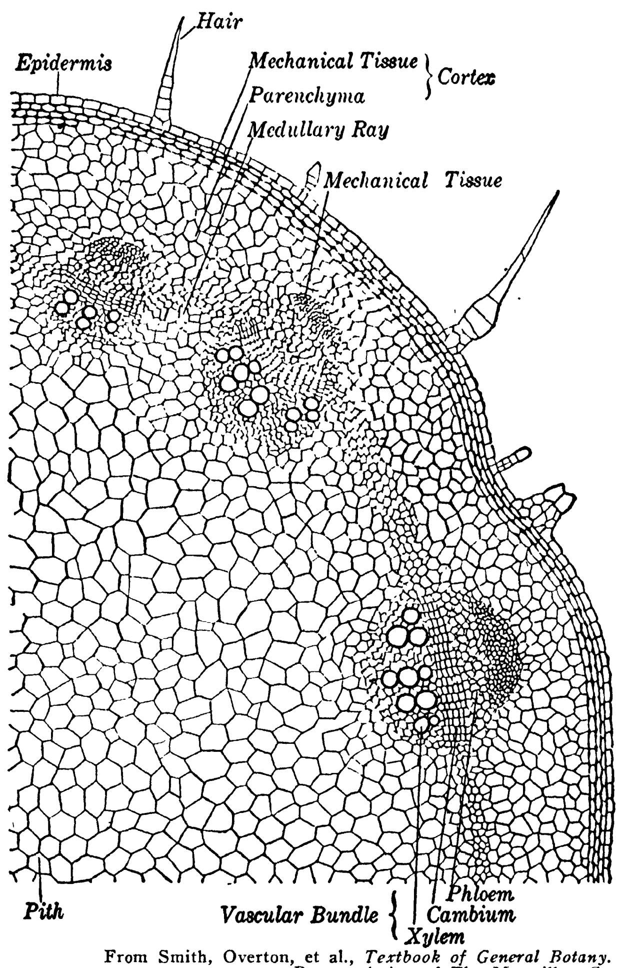
FIG. 137.—Relation of root-hairs to the soil. co, cortex; e, epidermis. Root-hair: n, nucleus; cy, cytoplasm; cw, cell wall. Soil: s, soil particle; w, water; a, air.

the leaves, forming a continuous system of channels throughout the plant. In addition to ducts and sieve tubes, most vascular bundles contain considerable sclerenchyma tissue. In fact, much of the strength and flexibility of the stem and its branches is due to the mechanical properties of the vascular bundles.

Microscopic Structure of a Stem. The tissues of the stem are organized around the vascular bundles, although the arrangement of the bundles differs considerably in different plants. Main attention will be given to the stem of a sunflower plant, which is quite typical of the *young* stems of dicotyledonous plants generally.

In cross-section, the sunflower stem displays a circular arrangement of the *vascular bundles* (Fig. 138). Accordingly, it

is possible to subdivide the stem into three concentric regions: (1) the *pith*, a central core of colorless parenchyma; (2) the



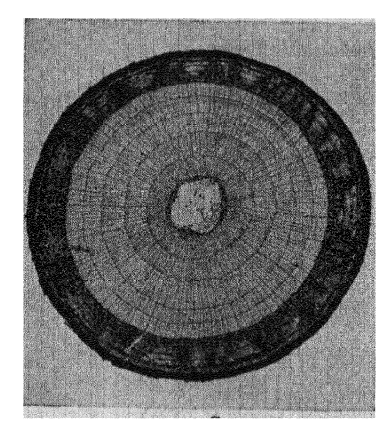
From Smith, Overton, et al., *Textbook of General Botany*. By permission of The Macmillan Co.

FIG. 138.—Cross-section of a sunflower stem.

vascular region, comprised by the ring of bundles, taken collectively; and (3) the *cortex*, the tissues which surround the ring of bundles.

Figure 138 shows that each vascular bundle is subdivided into

an inner part, the *xylem*, and an outer part, the *phloem*, by the *cambium*, a layer of meristem tissue. All growth in the girth of the stem results from the activity of the cambium cells, which keep multiplying and differentiating to form the other tissues. New phloem—which consists mainly of sieve tubes—is formed along the *outer* margin of the cambium; and new xylem—mainly ducts—is formed by the cambium along its *inner* margin.



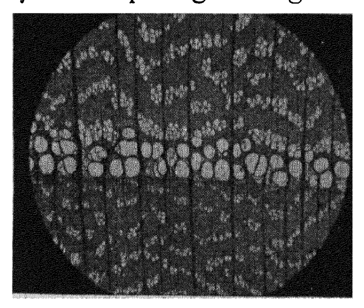
Courtesy of Triarch Botanical Supplies

FIG. 139.—Cross-section of linden (Tilia americana) stem. The central pith is surrounded by five *annual rings* of xylem, which is bounded in turn by the phloem and a corky cortex.

Surrounding the vascular region lie the tissues of the *cortex*, which commonly is called the bark; and between the bundles, lies the *medullary rays*, i.e., the strands of tissue which extend radially from the pith to the cortex (Fig. 132). The cortex, together with its superficial layer of *epidermis*, serves chiefly as a protective cover, although in young stems the cortex may contain chlorenchyma and perform a limited amount of photosynthesis. The *pith* consists of colorless parenchyma, in which the large thin-walled cells serve as storage centers, chiefly of starch grains. In older stems, the cells of the medullary rays become elongate in a horizontal direction, which indicates that the rays act as channels for the radial distribution of substances, from the vascular tissues outward into the cortex and inward into the pith.

During the first year of growth, *woody stems* such as are characteristic of most trees and shrubs closely resemble the sunflower stem. But in woody stems, the cambium gives rise each year to an additional layer of xylem on the inside, and another (much thinner) layer of phloem on the outside. These yearly deposits of xylem in woody stems are clearly differenti-

ated as the *annual rings* (Fig. 139). The annual rings are distinguishable because the ducts which are formed in the spring of each year are larger than those which are formed in summer; and because fewer wood fibers (p. 285) are formed during the spring growth of the xylem (Fig. 140). Only the outermost or youngest layer of the xylem continues to carry sap upwards through the plant, but the older xylem keeps augmenting the strength of the stem as the load of foliage becomes greater. Woody stems also tend to develop a "corky" layer outside of the cortex proper, and this cork replaces the epidermis (Fig. 139). Moreover the thickness of the bark does not increase indefinitely because the outer layers are continually worn away by the action of the elements.



From Fuller, *The Plant World*. Photo by O. Tippo

FIG. 140.—Photomicrograph of a cross-section of the wood of elm (Ulmus americana). The light circles are ducts, between which lie chiefly wood fibers; and the vertical streaks are medullary rays.

Conduction in the Stem. The upward flow of sap in the *xylem*, which carries water and salts to the higher parts of the plant, can be demonstrated by girdling experiments. If a cut is made through the cortex and phloem, encircling the stem just to the depth of the cambium, the leaves of the plant remain turgid and do not wilt for a number of days. This shows that water passes the girdled region and reaches the foliage in adequate amounts. However, growth in the stem and roots *below* the cut stops as soon as the local stores of organic substances are exhausted. Finally the roots begin to die, and then the whole plant dies—which indicates that the roots and other non-leafy parts of the plant depend upon synthesized organic substances brought *downward* from the leaves via the *sieve tubes* of the phloem.

Internal girdling, which is the opposite experiment, involves cutting the xylem of a stem without disturbing the phloem.

This operation is difficult, but it can be done in small stems, by means of special instruments. The leaves of such a girdled plant begin to wilt and die immediately after the operation, because water cannot get to the leaves to replace the evaporative losses. And without leaves the whole plant will die, unless it can put forth new foliage from the stem below the level of the operation.

The Leaf and its Function. The broad blade-like form of typical leaves is well adapted to their function—which is to carry on photosynthesis for the plant as a whole. To fulfill this function the leaf must possess an adequate surface which is exposed as directly as possible to sunlight.

The leaf in dicotyledonous plants consists of a stalk, called the *petiole*, and a broad part, the *blade*, which may be either simple, or subdivided into leaflets. In structure the petiole closely resembles the stem; and the vascular bundles of the petiole extend out into the blade, forming the *midrib* of the leaf. In the blade the vascular bundles of the midrib "fan out," forming a network of *veins* throughout all of the blade. Essentially each vein is a small vascular bundle, surrounded by a sheath of parenchyma cells.

Microscopic Structure of a Leaf. The internal structure of the leaf is seen more clearly in *cross-section* (Figs. 141 and 142). The colorless cells of the upper and lower epidermis possess relatively thick, thoroughly cutinized outer cell walls. This epidermal layer protects the more delicate internal cells from drying and from mechanical injuries and infections. The epidermis, especially on the lower side of the leaf, is characterized by the presence of numerous small pores, the *stomata*. Each stoma is flanked by a pair of *guard cells* (Figs. 141 and 142), which control the escape of water vapor, and regulate the exchange of CO_2 and O_2 between the internal tissues and the atmosphere. Unlike epidermal cells, the guard cells possess chloroplasts.

Most of the space between the upper and lower epidermis is filled with chlorenchyma tissue; but these green cells are loosely arranged, especially in the lower layers (Fig. 141). Accordingly there is an extensive system of intercellular air spaces inside

the leaf, and these internal air spaces communicate with the outside air through the stomata.

The network of veins, or vascular bundles, in the leaf is so extensive that one or more bundles is likely to be present in any section of the leaf, however small (Fig. 142). The xylem of each vein occupies an upper position relative to the phloem; and the smaller veins may consist of only a few ducts and a

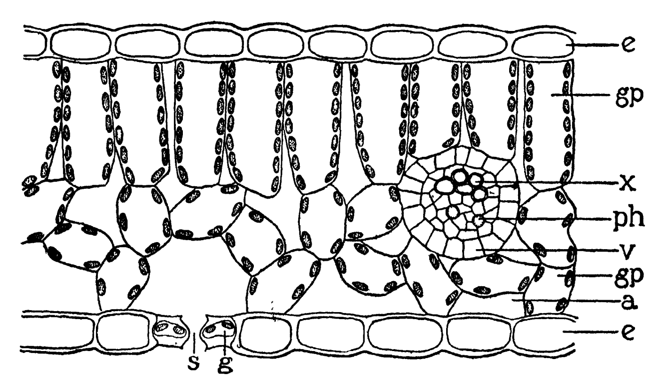
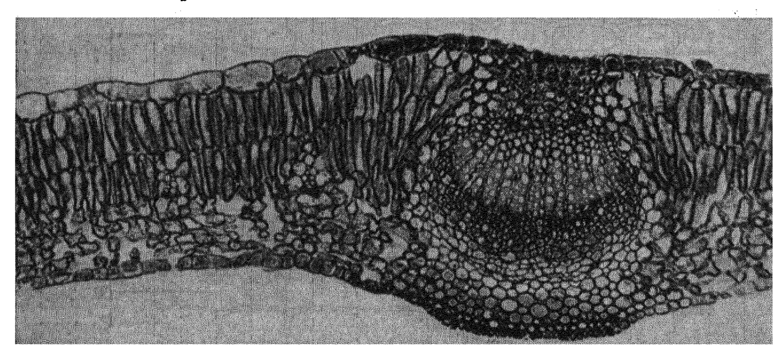


FIG. 141.—Cross-section of portion of the blade of a leaf, including a single vein. e, epidermis, gp, green parenchyma (chlorenchyma) cells, containing chloroplasts; a, intercellular air space; s, stoma; g, guard-cell. Vein: x, xylem; ph, phloem; v, sheath of vein.

corresponding number of sieve tubes. The very smallest veins—out near the margin of the blade—lack sieve tubes and consist of only one or two ducts, which end blindly among the chlorenchyma cells. As in the stem, the vascular bundles of the leaf are chiefly channels of distribution. Water and salts are brought to the chlorenchyma cells by the ducts, and organic substances are carried out of the leaf by the sieve tubes.

Transpiration. On sunny days the leaves give off large amounts of water vapor, provided the plant is able to absorb a compensating quantity of water from the soil. This loss of water vapor from the leaves, which is controlled by the guard cells, is called *transpiration.* The heat of the sun keeps vaporizing water from the surfaces of the thin-walled chlorenchyma cells inside the leaf, and the resulting vapor passes out of the leaf by way of the stomatal openings.

In most leaves the stomata occur chiefly or entirely on the lower surface; and the number of stomata varies between 50-500 per square millimeter of the surface (Fig. 131). The average size at maximal opening is about 6 x 18 microns, so that about 1/20 of the leaf surface may be occupied by stomata. The transmission of gases through such a perforated membrane is almost as rapid as in free diffusion. However, the size of the



Courtesy of Triarch Botanical Supplies

FIG. 142.—Photograph of a cross-section of a lilac leaf. One large vein lies in the thick part of the section, and two very small veins are present in the thinner part to the left.

stomata is regulated strictly by the guard cells. When plenty of water comes up to the leaf from the soil, the guard cells remain turgid; and when turgid, the guard cells spring apart opening the stomata (Fig. 143). But when the loss of water by transpiration exceeds the gain of water from the soil, the guard cells wilt, and the wilted guard cells change shape in such a fashion that they block the stomatal openings. The guard cells possess chloroplasts, which enable them to regulate their own turgor according to current conditions. By synthesizing sugar, the cells may increase their turgor; or by converting sugar into starch, the cells may lose turgor. Accordingly the stomata tend to remain open in the daytime—providing the water supply is adequate; but at night they tend to be partially closed.

The quantity of water transpired by an average plant in sunlight is about 50 grams per square meter of leaf surface per

hour. Thus a single corn plant puts forth more than 50 gallons of water in the course of one summer; or an acre of corn transpires about 300,000 gallons of water in the same time. An average tree transpires more than 1,500 gallons annually; and the total quantity of water vaporized from the vegetation of a

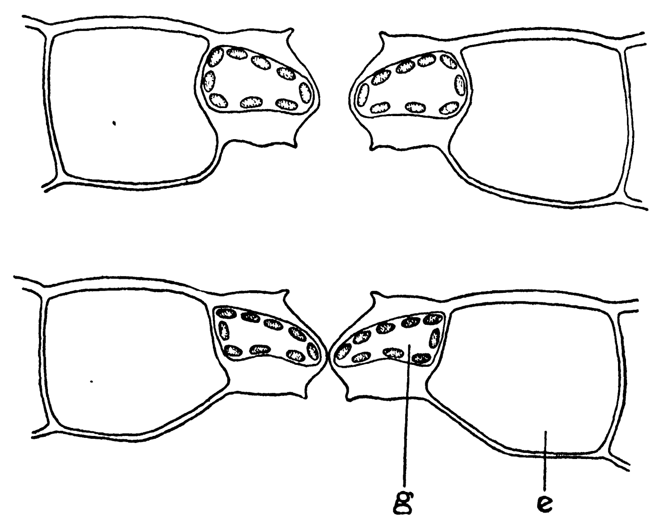


FIG. 143.—The action of guard cells. Above, the guard cells are turgid, leaving the stoma open; below, the guard cells wilted (i.e., less turgid), closing the stoma. g, guard cell, containing chloroplasts; e, ordinary epidermal cell, without chloroplasts.

forestrated region has a significant influence upon the rainfall, humidity and temperature of that region.

As the sun beats down, the leaf absorbs about 75 per cent of the impinging light. Most of this light is absorbed by the chloroplasts, but only about 3 per cent of this energy is utilized in photosynthesis. The rest is transformed into heat—the heat which vaporizes water and leads to transpiration. This vaporization is most important, not only because it dissipates the heat which otherwise would kill the tissues of the leaf, but also because it generates an osmotic force which evacuates the ducts of the leaf, facilitating a further flow of sap from the roots.

Transpiration and the Flow of Sap. Transpiration facilitates the upward flow of sap by altering osmotic conditions in

the leaves. When the chlorenchyma tissues lose water, the cells become hypertonic to the sap in the veins, which lie in direct contact with the chlorenchyma (Fig. 141). During transpiration consequently, water tends to be drawn from the ducts into the chlorenchyma tissues. Such a forceful evacuation of the ducts of the leaf allows more sap to enter from the ducts of the stem and roots. But more important still, the osmotic evacuation of the leaf ducts creates a lifting force which helps to elevate the whole column of sap which is ascending from the roots. Consequently transpiration greatly accelerates and facilitates the flow of sap in all plants. Such a large flow is not necessary to provide water for photosynthesis, for actually only about 1 per cent of the water reaching the leaf is used this way. But a very copious flow is necessary if the leaf cells are to receive adequate quantities of salts (for protein synthesis), since only very small amounts of inorganic salts are present in the sap. Moreover, large quantities of water are needed in the leaf to prevent an overheating of the tissues.

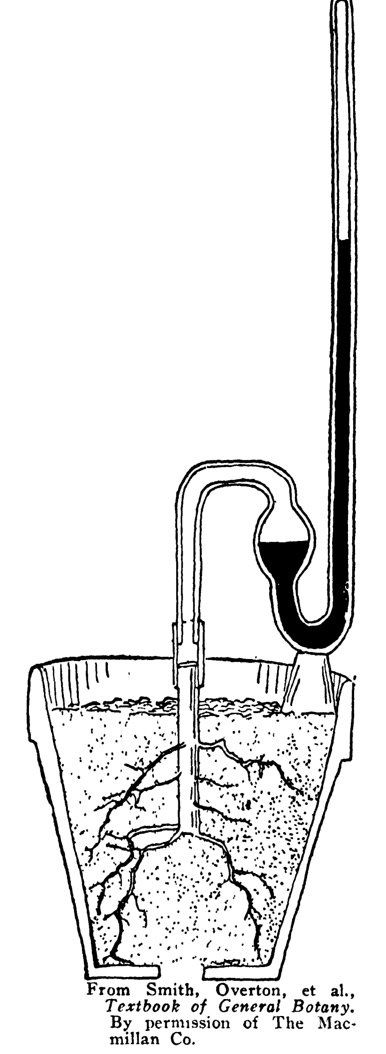
Elevation of Sap in Tall Trees. The rise of sap in tall trees—which may grow to heights of more than 300 feet—involves the cooperation of both *transpiration* and *root pressure.* Root pressure is the positive pressure of the sap in the ducts at the point where these vessels emerge from the root to enter the stem. Root pressure is measured by cutting off the stem close to the root and joining the base of the stem to a pressure gauge, which records the force built up by the exuding sap (Fig. 144). Technical difficulty is encountered in making a junction which is both leak-proof and non-injurious to the tissues in the region of the joint; and on this account early investigators failed to record pressures which were adequate to lift the sap to any significant height. However, recent experiments prove that even a small plant, such as the tomato, can generate a root pressure of about 12 atmospheres—which is sufficient to raise the sap to a height of 384 feet.

Root pressure arises from the hypertonicity of the root sap, relative to the soil water which surrounds the root. A 10 per cent glucose solution separated from soil water by a membrane

which is permeable to water but not to the sugar, will continue to absorb water until a pressure of more than 12 atmospheres has been developed. In the root, the semipermeable membrane is provided, not by the walls of the ducts—since these vessels are non-living—but by the layers of living cells which intervene between the ducts and the external surface of the root (Fig. 136).

In the intact plant, transpiration also participates in the lifting of the sap. The constant evaporation of water from the leaves—and the fact that the leaves produce considerable sugar —keep the chlorenchyma cells distinctly hypertonic to the sap in the veins. Consequently the chlorenchyma continually draws water from the upper parts of the ducts, and this evacuation tends to *lift* the column of sap upwards in each duct. This lifting power of transpiration can be observed in a leafy branch which has been cut from a plant and placed in water. In such a branch, the leaves continue to transpire, and can draw up enough water to maintain a normal turgor in the tissues for several days.

In the springtime, before leaves have developed on the



From Smith, Overton, et al., *Textbook of General Botany.* By permission of The Macmillan Co.

FIG. 144.—Root pressure. The stem of a potted geranium was cut off and replaced by a closed tube containing mercury. Sap exudes from the stem, forcing the mercury upward, compressing the air in the tube.

branches, a tree depends entirely upon root pressure for the large amounts of water needed by the sprouting buds. At this time the sugar content—and hence the hypertonicity of the root sap—reaches a maximum, because the winter stores of starch in the root parenchyma are converted in the spring to sugar, which passes into the ducts. But in summer, the solute content of the root sap depends mainly upon the small amount of sugar which gradually comes down to the roots from the leaves. Consequently, in summer root pressure is relatively low, and the plant depends more largely upon the lifting power of transpiration.

Distribution of Organic Substances in Plants. Part of the glucose and other organic substances synthesized in the leaf are utilized in the metabolism of the cells of the leaf itself. But a greater part passes from the leaves to the lower parts of the plant, mainly via the sieve tubes of phloem.

The sieve-tubes convey organic nutrients at a relatively slow rate—depending partly upon diffusion from cell to cell through the sieve-plates which interrupt the columns (p. 285); and partly upon the rate of streaming in the protoplasm of the sieve-tube cells. As sugars and other soluble products pass downward through the stem, some may diffuse radially, supplying the tissues at each level. The medullary rays in thicker stems facilitate this radial distribution to the cells of the pith, which tend to accumulate large reserves of starch. The remaining organic products eventually reach the root parenchyma, which also stores large quantities of starch, especially in the case of perennial plants.

Metabolism in Higher Plants. Metabolism goes on in all the living cells of the plant—producing new organic substances needed for the growth and maintenance of the tissues—and providing energy, without which the synthetic and responsive activities of the plant could not proceed.

The mainspring of *constructive* metabolism is photosynthesis, which is effected chiefly in the leaves. The leaves produce glucose for the whole plant; and glucose is the primary source of matter and energy in all the cells.

Under average conditions the amount of glucose produced in a leaf is about 1 gram per square meter of surface per hour of daylight. In the present period of geological time one limiting factor imposed upon the rate of photosynthesis is the relatively small concentration (about 0.03 per cent) of CO_2 in the atmosphere; and if a greater amount (up to 10 per cent) of CO_2 be provided artificially, the rate of photosynthesis can be accelerated considerably. This, in fact, is part of the evidence indicating that the tremendous growth of vegetation which occurred during the era when our coal deposits were formed resulted from a higher content of CO_2 in the terrestrial atmosphere.

In daylight, the production of glucose exceeds the rate at which sugar can be evacuated from the leaf; and the excess is converted into starch in the chlorenchyma cells. At sunset, accordingly, the leaf contains an abundance of starch—as can be demonstrated by the iodine test. But at sunrise the test is apt to be negative. During the night the temporary deposits of starch are reconverted to glucose, which gradually passes from the leaf to other parts of the plant.

Aside from photosynthesis, constructive metabolism is essentially similar in the different tissues of the plant. Given glucose, together with nitrates, sulfates, phosphates and other inorganic salts, plant cells can synthesize all the different amino acids; and from the amino acids, by dehydration synthesis, each cell forms the specific proteins which are essential to its protoplasmic structure. Although all the cells of a plant can synthesize amino acids, the chlorenchyma cells—having a more direct supply of glucose—are in a specially favorable position. Accordingly the green tissues of the plant tend to produce extra amino acids and to transmit the extra amounts to the lower parts of the plant via the sieve tubes.

Plant cells also can convert glucose into fats and steroids; and if phosphates and other salts are available, glucose can be converted into phospholipids. Thus it may be said that plants use glucose as a source of carbon, hydrogen and oxygen in synthesizing all their organic requirements, including such other compounds as vitamins, special drugs, perfumes, etc. (p. 306).

Destructive metabolism is relatively simple, because plants derive most of their energy from the oxidation of glucose. Plants tend to limit their synthesis of proteins, lipids and other structural components of the protoplasm to such amounts as are needed for growth and maintenance, and consequently plants do not usually possess excesses of these structural compounds for use as fuel. During periods of malnutrition, i.e., when the light, water, or salts are inadequate, plants may sacrifice some of their proteins and other essential compounds in order to obtain energy for maintaining the protoplasmic structure—but this last resort postpones death only for a short while. Ordinarily plants derive virtually all energy from carbohydrates; and consequently the end-products of plant catabolism are mainly CO_2 and H_2O.

Because of photosynthesis, the constructive metabolism of plants greatly exceeds destructive metabolism. In growing, an average plant oxidizes only about 15 per cent of its photosynthesized glucose. This oxidized glucose liberates enough energy to convert the remaining glucose: into starch (about 50 per cent); into cellulose and related compounds (about 25 per cent); and into the carbon-hydrogen-oxygen parts of proteins and other essential compounds (about 10 per cent). Inevitably, therefore, plant growth represents a net increase of organic matter in which the stores of useful energy are derived entirely from the sun.

Respiration in Higher Plants. Each organ of the plant takes in oxygen and gives off carbon dioxide mainly on a local basis. All the cells use oxygen and produce carbon dioxide, as oxidative metabolism proceeds, and consequently respiration must occur in all the organs.

The leaves differ from the stem and roots, because, during photosynthesis the leaves produce more oxygen than they use in oxidative metabolism. Likewise leaves in daylight consume more carbon dioxide than they form. Consequently the gas exchange of photosynthesis overrides that of respiration in the leaves of the plant during the daylight hours. However, the stem and root, and the leaves at night, must obtain oxygen from

the outside, and must get rid of carbon dioxide; and this respiratory gas exchange takes place through air spaces in the loosely packed parenchyma tissues (Fig. 145). These air spaces

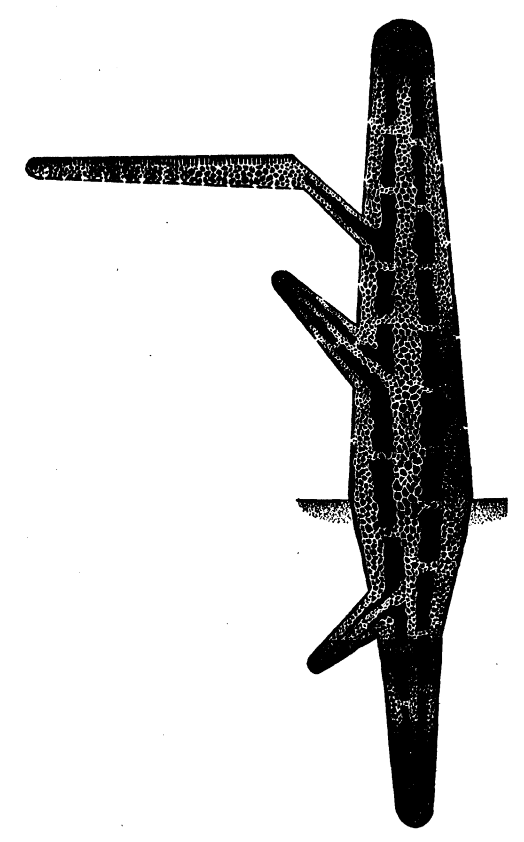


FIG. 145.—Diagram of the aeration system of a vascular plant. The white lines represent intercellular air spaces, opening to the outside through stomata. (Adapted from Ganong.)

form a continuous system throughout the plant; and in the leaves and stem, the air spaces communicate with the outside atmosphere through stomata. Roots have no stomata, but the respiratory gases are exchanged by osmosis between the root tissues and the soil water. Well-aerated soil contains 20-40 per cent (by volume) of air, and this air maintains equilibrium with

the soil water, which clings to the loosely packed soil-particles. Closely packed soils—or swampy soils in which the air spaces are filled with water—are ill-suited to most plants, because these conditions tend to asphyxiate the roots, eventually killing the whole plant. Likewise a heaping of soil around the lower parts of the stem may cause asphyxiation. Each part of the plant must breath for itself; and the movements of the respiratory gases depend entirely upon diffusion and osmosis. However, the oxygen requirements of plants are comparatively modest; and each plant, as a whole, produces more oxygen than it uses.

Excretion. Aside from oxygen, the metabolic end-products of plants are chiefly water and carbon dioxide—the very substances that serve as raw materials for photosynthesis. To a large extent the plant utilizes its own products of combustion; and excretion is relatively small. The small amount of metabolically formed water may remain in the plant until it is utilized; or it may be passed off by osmosis or transpiration.

In plants, it is difficult to define the metabolic wastes and to differentiate between excretion and secretion. Many flowers and some leaves give off sweet and fragrant substances in the form of *nectar*, which may be partially excretory in nature. Some plant cells tend to accumlate organic acids, especially oxalic acid, which may precipitate in the vacuoles as crystals of the calcium salt. Such crystals usually are formed in the leaves or bark, where disposal occurs—by the shedding of the leaves or the wearing of the bark.

Storage Problems Among the Plants. The storage of reserve organic products is largely a matter of self-preservation for the individual plant, although if plants had not developed this capacity, much of the food which supports the animal kingdom—including mankind—would not be produced. The individual plant accumulates organic reserves to tide it over periods when photosynthesis cannot be carried on. Among seed plants, for example, the embryo cannot grow independently until the seed has sprouted and the new sporophyte has developed a functional root, stem and leaf system. Accordingly the parent plant deposits a reserve of organic substances in the seed and fre-

quently in the surrounding fruit structures as well. Deciduous plants, which shed their leaves each season, also depend upon organic reserves laid down in the stems and roots. In the spring, deciduous plants use these organic reserves for the matter and energy utilized in the growth of the new foliage.

The most abundant organic reserve in the plant kingdom is starch; and the starch grains of different plants display many characteristic variations of size and form. Given starch—or glucose derived by hydrolysis from starch—plants can synthesize all their growth requirements, provided inorganic salts and oxygen are also available. In addition to starch, some seeds contain fat globules and crystals of reserve proteins in the cells of the cotyledons. Reserve proteins permit the embryo to grow more extensively prior to the time when the roots develop a capacity to absorb an adequate quantity of nitrates and other inorganic salts. In perennial plants, reserve starch is deposited mainly in the colorless parenchyma: more or less equally in the stem and root; or predominately in the stem, or root, depending on the species.

Economic Importance of Plant Products. The importance of plant products, as direct sources of man's food, and in the sustenance of animals which in turn become man's food, is altogether inestimable. Plant *seeds* (corn, wheat, oats, barley, rye, rice, and a wide variety of nuts) and fruits (apples, oranges, eggplant, squash, pumpkin, etc.) have a worldwide cultivation and give tremendous yields. *Roots* (beets, carrots, parsnips, radishes, turnips, sweet potato, tapioca, etc.) and *stems* (sugar cane, sugar maple, white potato, onion, etc.) and finally *leaves* (lettuce, spinach, artichoke, cabbage, etc.) also provide a considerable quantity of man's needs. Moreover, leaves, especially the grasses, provide the staple food of all man's grazing livestock.

Many other economic values of plant products can also be enumerated: (1) *lumber*, for construction and other purposes; (2) *drugs*, such as aconite, asafetida and valerian (from roots); quinine, cascara and ephedrine (from stems); belladonna, cocaine and digitalis (from leaves); and castor and chalmoogra oils (from seeds); (3) *spices* and *flavors*, such as horse-radish,

sarsaparilla and sassafras (from roots); garlic and ginger (from stems); sage, wintergreen and thyme (from leaves); and anise, nutmeg and mustard (from seeds); and (4) miscellaneous other products, such as latex for rubber; oils, gums, resins and turpentine for paints, varnishes and soaps; cork for stoppers; fibers for ropes and fabrics; and many other items. Man has been very prodigal in his expenditure of *wild* plant resources, especially in the ravaging of forests. Only as to the cultivation of many selected plant species has man given a fair degree of reciprocity. Under cultivation a plant is assured of perpetuation; and man takes only the excess of the synthesized products.

TEST QUESTIONS

1. How do the "holdfasts" of the algae differ in structure and function from the true roots of higher plants?
2. What factors help to explain the fact that the algae have remained in a relatively undifferentiated state as compared to most terrestrial plants?
3. Compare the tissues of the Bryophytes with the corresponding tissues of the vascular plants. To what extent do these differences account for the greater "success" of the higher plants? Explain.
4. Identify: (a) meristem tissue; (b) epidermis; (c) chloremchyma; (d) storage parenchyma; (e) bast fibers; (f) wood fibers; (g) sieve tubes; (h) ducts; (i) xylem; (j) phlorm.
5. Specify the major nutritive organs of the vascular plants and explain the main functions of each.
6. Differentiate between woody and herbaceous stems.
7. A. Make labelled diagrams showing the essential features of:
    a. the one-year-old stem of a dicotyledenous plant, as seen in x-section;
    b. a rootlet (long section);
    c. a typical leaf (x-section).

    B. State the function or functions of each labelled part.
8. Define and discuss transpiration, emphasizing:
    a. how it is energized;
    b. its magnitude and how it is controlled;
    c. its effect upon the rise of sap;
    d. its relation to the leaf temperature.

9. Define and discuss root pressure, emphasizing:
    a. the fundamental nature of the phenomenon;
    b. how it is measured;
    c. how it is maintained;
    d. its effectiveness in elevating the sap.
10. Assuming that a plant has synthesized 100 grams of glucose, about how much of this matter would be:
    a. oxidized to provide energy for constructive metabolism;
    b. transformed into starch;
    c. transformed into cellulose;
    d. transformed (together with inorganic salts) into proteins and other structural components of the protoplasm?
11. Explain the importance of starch storage:
    a. from the plant "viewpoint";
    b. from the viewpoint of mankind.
12. Explain how respiration occurs in the leaves, stem and roots of a seed plant. Specify two conditions which frequently cause an asphyxiation of roots.

FURTHER READINGS

1. *Plant Physiology*, by B. M. Duggar; New York, 1927.
2. *The Physiology of Plants*, by William E. Seifriz; New York, 1938.
3. *The Plant World*, by Harry J. Fuller; New York, 1941.

CHAPTER 13

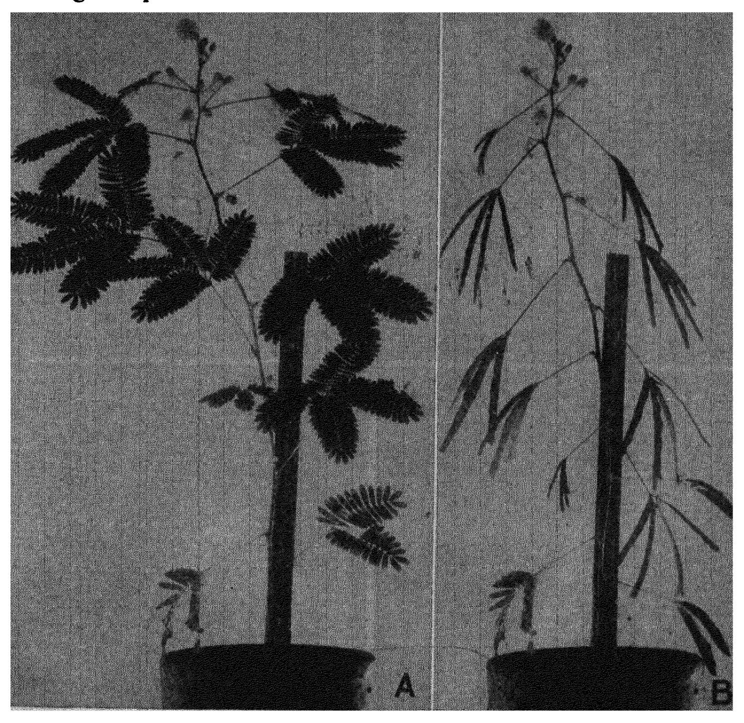
THE RESPONSES OF MULTICELLULAR PLANTS

THE MOVEMENTS of multicellular plants are seldom very quick or extensive; and consequently many plant responses escape the casual notice. This restriction of movement is due to the anchorage of plants to the soil and to the rigidity of plant tissues —but even the slow and limited movements of higher plants have considerable importance in the survival of the species.

Turgor Movements vs. Growth Movements. Among higher plants two general types of movement can be distinguished. *Growth movements*—such as the bending of stems toward light—are so slow that an hour or more is required to perceive a change; and once a growth movement has occurred, it is scarcely ever reversed. *Turgor movements,* in contrast, are relatively rapid and reversible—like the drooping of leaves during a rainfall. Such a difference in tempo and reversibility indicates a difference in the basic mechanism of these responses. Growth movements, in fact, depend upon an unequal rate of growth in the cells on opposite sides of the bending part; but turgor movements are effected by osmotic changes occurring in specialized effector cells (see below).

Turgor Movement. The rapid drooping of the leaves of a sensitive plant (*Mimosa puduca*) is a typical turgor movement. The normal position of the leaves of the plant is horizontal; but if one of the leaves is touched, even lightly, all the leaflets begin to fold up, and within 2 or 3 *seconds* the whole leaf droops to a marked degree. Or if a leaf is struck less gently, not only does the stimulated leaf fold and droop, but a wave of folding

and drooping spreads from the stimulated leaf to all neighboring leaves (Fig. 146). This response of the Mimosa is strictly reversible, and after about a minute, the plant slowly regains its original posture.



From MacDougall and Hegner, *Biology*, McGraw-Hill Book Co.

FIG. 146.—Response of the "sensitive plant," Mimosa pudica: A, before being touched; B, after being touched (Dr. E. H. Runyon).

The receptors, conductors and effectors of this response of Mimosa are strictly localized. The *excitation* (p. 206) originates in the epidermal cells of the leaf, which possess numerous tactile hairs projecting from the surface; and the excitation spreads, mainly along the sieve tubes. The excitation follows the course of the vascular bundles through the petiole to the point where the petiole joins the stem. Here lies the *pulvinus*, a cushion of cells which normally supports the leaf in a horizontal position.

When an excitation reaches the pulvinus, the pulvinus cells lose their turgor, relaxing their support of the leaf. Thus the pulvinus is the effector of the drooping response; and the sieve

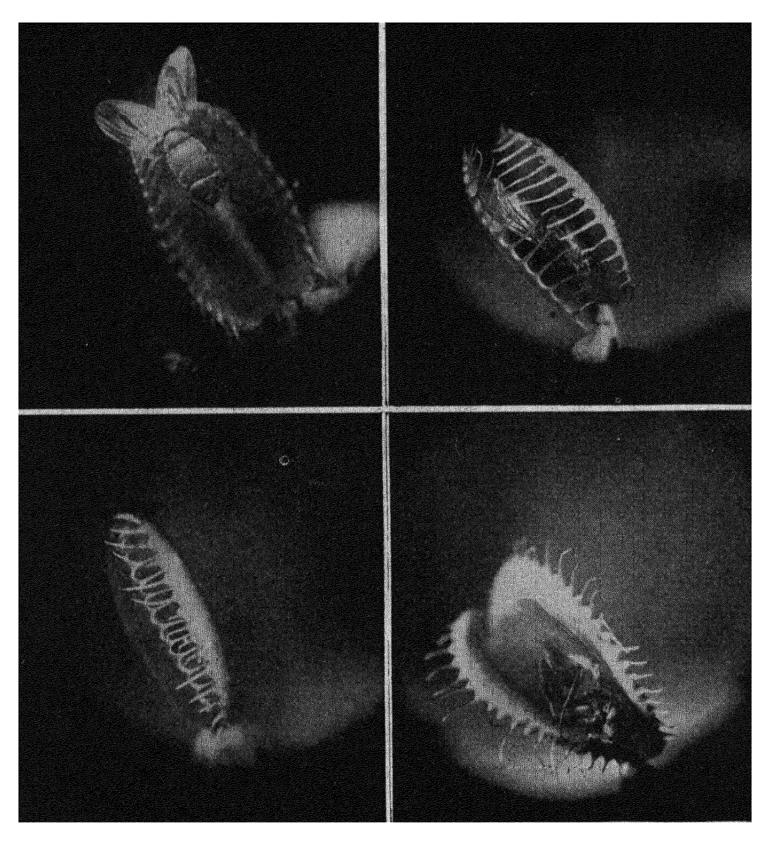
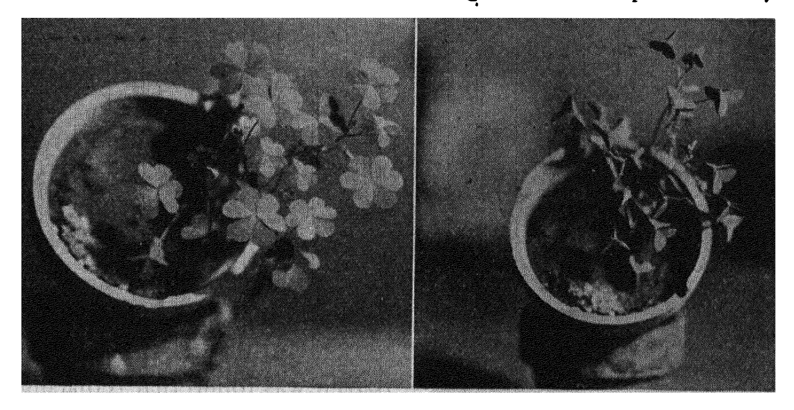


FIG. 147.—Venus's-flytrap (Dionaea) catching and digesting a fly.

tubes and epidermal cells, respectively, are the conductors and receptors.

Specialized receptor-conductor-effector structures in plants are less clearly defined than in animals, and consequently the responses of plants are less rapid and precise. The drooping of the Mimosa leaf is very rapid compared to most other plant responses, but even in this case the propagated excitation—as

timed by the spread of the action current—is transmitted at a rate of only about 5 centimeters per second (compared to 120 meters per second along the nerves of man). Nevertheless the basic nature of excitation and conduction appears to be similar in plants and animals. In both cases, the excitation may be blocked by narcotic agents; and in both plants and animals excitation is accompanied by a bio-electric discharge, increased permeability



From Fuller, *The Plant World*

FIG. 148.—Sleep movements in Oxalis stricta. Left, day position of leaflets; right, night position of leaflets.

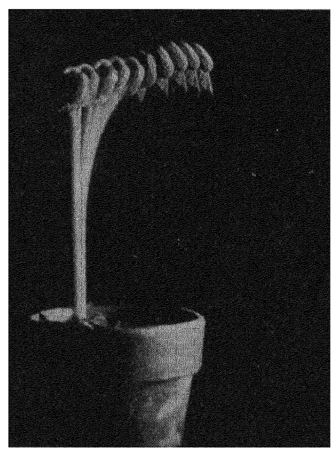
of the excited cells, and a temporary alteration of the local metabolism.

Other Turgor Movements. Although the evidence is somewhat scanty, it seems probable that other rapid and reversible responses in plants are turgor movements involving receptor-conductor-effector structures similar to those of Mimosa. Accordingly, (1) the drooping of leaves during rainfall; (2) the movements by which leaves and flowers follow the course of the sun; (3) the leaf-closing movements by which *insectivorous plants* trap their living prey (Fig. 147); and (4) the sleep movements of many plants (Fig. 148) are all considered as typical turgor movements.

Growth Movements. An example of growth movement is the bending of young stems toward a source of light (Fig. 149). Such growth movements proceed so slowly that about an hour

is required to appreciate the change; and growth movements tend to be irreversible. The bending depends upon a faster *lengthwise* growth of the cells on one side of the stem; and the convexity of the curvature always lies on the side of faster growth (Fig. 149).

The fundamental difference between growth and turgor movements was not clarified until 1910, when evidence began to accumulate proving the existence of *growth substances*, which regulate the growth of cells in different parts of the plant. Previously it was known that cutting off the meristem tissue at the tip of a stem stops growth in the cells of the stump, where normally the cells continue to *elongate* until they become fully differentiated. In 1910 it was found that replacing the decapitated tip of meristem tissue restores the growth of the cells of the stump. This effect was still obtained even when a fairly thick (2 mm.) layer of agar was interposed between the cut surfaces—which proved that some diffusible substance—rather than a wave of excitation—is responsible for the growth effect.

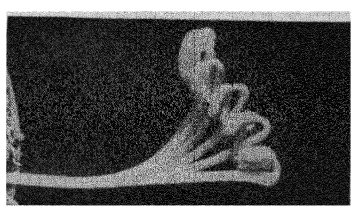


From Fuller, *The Plant World*

FIG. 149.—Positive phototropism of the stem of a bean seedling. Successive photographic exposures taken at 40-minute intervals.

The Auxins. Since these early experiments, three natural *growth substances*, or *auxins*, have been identified; and a variety of synthetic products have been found, which exert analogous effects. The three natural auxins—auxin a ($C_{18}H_{22}O_5$), auxin b ($C_{18}H_{30}O_4$), and heteroauxin ($C_{10}H_{15}NO_2$)—are all relatively simple, readily diffusible organic compounds; although heteroauxin has been obtained mainly from animal sources. All the natural auxins have been prepared in pure form, and all have been synthesized artificially. Virtually no specificity is found in

the action of the different compounds: i.e., all have similar effects when applied to corresponding parts of different plants. The auxins are produced primarily by meristem tissue in the growing points of the plant, whence they are transported to the nearby regions, where cell differentiation is occurring. The auxins, or phytohormones, may exert some influence on the rate of cell division; but their chief effect is to accelerate or, in some cases, to *retard*, the *lengthwise* growth of the individual cells.



From Fuller, *The Plant World*

FIG. 150.—Negative geotropism of a bean stem; successive photographs made on same plate at intervals of 45 minutes.

An important feature of the auxins is that their action upon the growth of stem and root cells is exactly opposite: lengthwise growth is *accelerated* in the stem but *retarded* in the root. When extra auxin is available—either under experimental or natural conditions—the stem elongates with unusual rapidity, whereas the root lengthens at a reduced rate. Thus if a poultice containing an auxin is applied to *one side* of a stem, faster growth occurs on that side, causing the stem to bend *away from* the site of application; but under similar treatment, the root bends *toward* the side where the extra auxin has been applied.

Tropisms. In both plants and animals the *direction* of many movements is determined by the *direction* from which the stimulus impinges upon the body. Stems generally bend toward a steady source of light, but roots turn away; and oppositely directed reactions are obtained when gravity is the stimulus (Figs. 121 and 150). Regardless of how these responses are effected, oriented movements, in which the direction is determined by the orientation of the stimulus, are called *tropisms*.

Movements directed toward and away from the source of stimulation are designated respectively, as positive and negative tropisms. Accordingly one speaks of the positive *phototropism* of leaves and stems, the positive *geotropism* and *hydrotropism*

of roots, the negative geotropism of stems, and the negative phototropism of roots.

In plants most tropisms are growth movements, in which the curvature results from an unequal distribution of auxins to the sides of the growing part. For example, when a primary root is placed in a horizontal position (Fig. 151), gradually a curvature develops as the rootlet grows longer, and finally the tip turns straight downward, toward the gravitational center

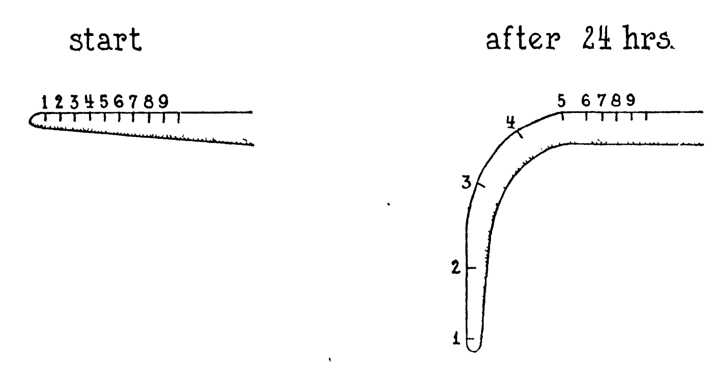


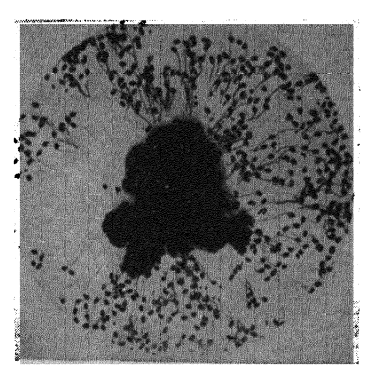
FIG. 151.—Positive geotropism in a root. The curvature results from a slower growth (elongation) of the cells on the lower side of the root.

of the earth. In this response it can be proved that more auxin is conveyed to the cells on the *lower* side of the root, and that the curvature is due to an inhibiting action of auxin upon the growth of the cells on this side of the root. Just how an unequal distribution of the growth substances occurs has not been demonstrated; but without auxin no curvature takes place. If the meristem of the growing point is removed by decapitating the rootlet about 1 mm. above the tip, the responsiveness of the root to gravity is abolished.

The negative geotropism of the *stem* is also effected on a similar basis. In the case of the stem, however, auxin *stimulates* growth. Greater concentrations of auxin are conveyed to the lower side of the stem, and consequently the stem bends upward rather than downward (Fig. 150).

Likewise the positive phototropism of the stem and the nega-

tive phototropism of the root are explained by the effects of light upon the auxin distribution in the plant. The growing point sends more auxin to the darker side of the stem or root, although *why* this occurs has not been demonstrated. In the stem, the stimulating effect of the auxin produces a curvature toward the source of light; whereas in the root, the inhibiting effect gives a bending in the opposite direction.



From Fuller, *The Plant World*

FIG. 152.—Positive chemotropism of pollen tubes, which are growing toward a crushed stigma.

Many other tropisms also depend upon the auxins. *Chemotropisms,* such as the growth of pollen tubes through the style (Fig. 152), or the growth of roots toward water (Fig. 153); and *thigmotropisms,* such as the twining of the tendrils of climbing plants around solid supporting objects—all appear to be typical growth movements, although these reactions have not been studied very intensively. However, some plant tropisms—such as the turning of leaves in following the course of the sun—appear to be turgor movements, involving receptor-conductor-effector structures which are generally similar to those of Mimosa.

Practical Importance of Auxins and Other Growth Substances. Auxins are now being used to initiate the development of roots in plants which are grown from cuttings; and promising results are being obtained in other directions. Auxins are used to foster the "taking" of grafts; and auxin-treated seeds (in certain species) germinate more successfully than untreated ones. With sugar beets, for example, the yield has been increased by about 60 per cent, although this effect is probably due to a stimulation of the growth of the seedlings, rather than to a direct action on germination. Auxins may also prove to be important in the development of fruits. In most species, the fruit fails to develop properly unless pollination has occurred;

but in the tomato at least, the application of auxins has yielded well-developed seedless fruits from unpollinated flowers.

To a very large extent the vitamins of animals (Chap. 17) are synthesized initially in plants, and in plant cells these substances have a definite bearing on growth. Recently it was found that flax roots—when cut from the plant and grown in

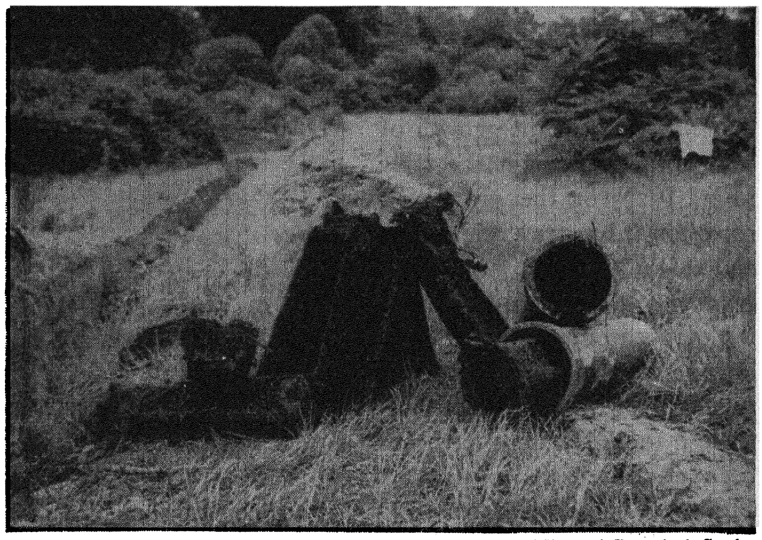


Photo by Missouri Botanical Garden

FIG. 153.—Positive hydrotropism. These roots entered cracks in the drain pipes and stopped them up.

an artificial nutrient solution—cannot grow in the absence of vitamin B_1 (p. 442); and that tomato roots require vitamin B_6 as well as B_1. In the intact plant these substances are synthesized largely in the leafy parts and sent to the lower parts to fulfill their physiological functions. Judging from the known role of the B-vitamins in animal cells—where they are essential components of several oxidizing enzymes—these compounds stimulate growth by assuring the energy supply of the growing tissues. Possibly the same holds true for the auxins also—in view of recent experiments which indicate that plant tissues, when deprived of auxin, cannot utilize some fuels which normally they oxidize quite readily.

TEST QUESTIONS

1. Explain two essential differences between growth movements and turgor movements.
2. Analyze the mechanical response of a sensitive plant in terms of the receptors, conductors, and effectors of the system. Why is this movement called a turgor movement?
3. Describe and explain the experiments which first demonstrated the existence of a *growth substance*, or *auxin*.
4. How do roots and stems differ in regard to their responses to the auxins?
5. A. What is a tropism?
   B. Explain precisely how the behavior of auxin helps to explain:
      a. the positive phototropisms of stems;
      b. the negative phototropisms of roots;
      c. the positive geotropisms of roots;
      d. the negative geotropisms of stems;
      e. other tropisms.

FURTHER READINGS

1. *Plant Growth-substances*, by Hugh Nicol; London, 1938.
2. *Phytohormones*, by F. W. Went and K. V. Themann; New York, 1937.

PART III

MULTICELLULAR ANIMALS, ESPECIALLY MAN

CHAPTER 14

EMBRYONIC DEVELOPMENT; ORIGIN OF THE ORGANS AND TISSUES

MULTICELLULAR animals generally seem quite alike at the outset of development. Each individual starts out as a single cell, the zygote; and most of the special features which differentiate the adult species do not appear until relatively late in embryonic development.

Fertilization. Each parent contributes only a single cell to the living matter of the offspring. Usually the *female gamete*, or *unfertilized egg*, is a large non-motile cell, with an abundant yolk-laden cytoplasm (Figs. 154 and 156). The nucleus of the unfertilized egg is haploid since each egg, together with three smaller cells, or *polar bodies*, is formed meiotically from one of the oöcytes of the ovary. The polar bodies (Fig. 156) are also haploid cells; but polar bodies contain very little cytoplasm, and are not capable of completing embryonic development.

The *male gametes*, or *sperm cells*, are usually small and motile (Fig. 157). Typically the *flagellum*, or *tail*, is joined to the *head*, by a small segment, the *middle-piece*. The head consists largely of a *nucleus* which, like the egg nucleus, is *haploid.*

Four sperm are produced by meiosis from each of the many primary spermatocytes in the testes.

Most *aquatic* animals discharge their eggs and sperm into the surrounding water; and the gametes come together more or less by chance. Such animals produce thousands or even millions of eggs and many times as many sperm. The sperm are usually discharged in the general vicinity of where the eggs are laid;

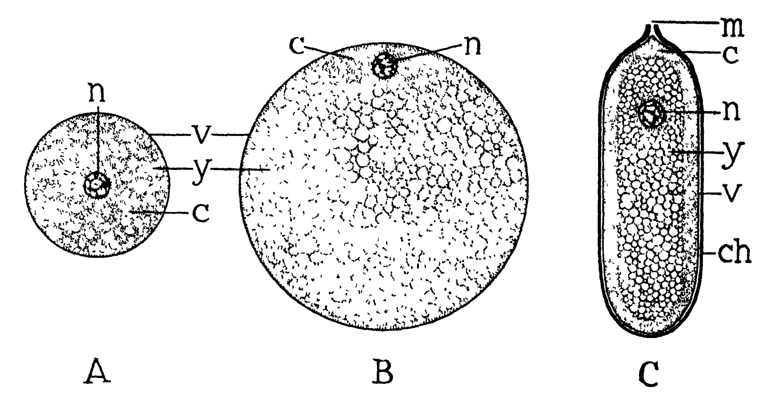
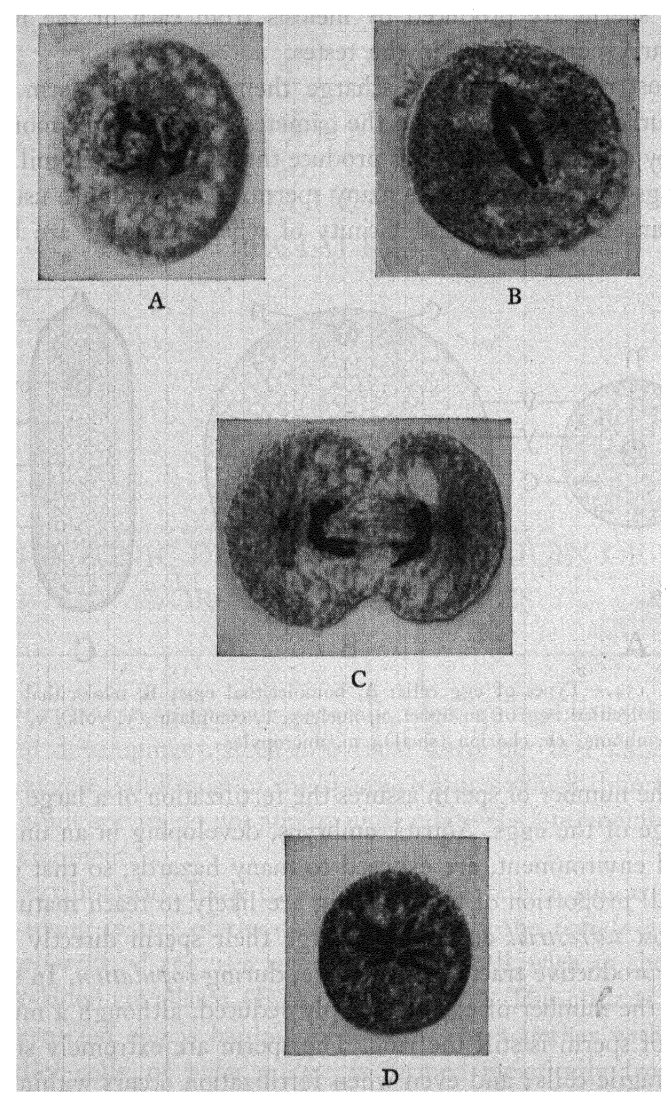


FIG. 154.—Types of egg cells: A, homolecithal egg; B, telolecithal egg; C, centrolecithal egg of an insect. n, nucleus; c, cytoplasm; y, yolk; v, vitelline membrane; ch, chorion (shell); m, micropyle.

and the number of sperm assures the fertilization of a large percentage of the eggs. Aquatic embryos, developing in an unprotected environment, are exposed to many hazards, so that only a small proportion of the offspring are likely to reach maturity.

Most *terrestrial* animals discharge their sperm directly into the reproductive tract of the female, during *copulation.* In such cases, the number of eggs is sharply reduced, although a multitude of sperm is still the rule. The sperm are extremely small and fragile cells; and even when fertilization occurs within the relatively narrow limits of the female reproductive tract, the distance traveled by a sperm is very great in terms of its own size. Consequently many sperm are required if a few are to succeed in reaching the eggs.

The contact of a sperm with an egg of the same species stimulates the egg to respond almost instantaneously. In some cases



Copyright General Biological Supply House, Chicago

FIG. 155.—Fertilization and cleavage in a roundworm (Ascaris). A, fertilization proper: the egg and sperm nuclei fuse to form the diploid zygote nucleus which (in this case) bears two chromosomes from the female parent and two from the male parent. B, early anaphase of the first cleavage. C, telophase of the first cleavage. D, polar view of the metaphase of the first division, showing the two pairs of chromosomes of the zygote.

From Marsland and Brandwein, *Manual of Biology*

FIG. 156.—Fertilization and early development of a homolethical egg (Starfish). A, *unfertilized egg*, showing the three *polar bodies* near the top; B, shortly after the head of a sperm has penetrated the egg, showing the fertilization membrane (around the egg), the tail of the sperm (protruding at the top), and the *entrance cone* of cytoplasm which has engulfed the sperm head (subjacent to the tail); C, two-cell stage; D, four-cell stage; E, eight-cell stage; F, many-celled hollow blastula; G, early gastrula, showing the invagination of endoderm in the vegetal part of embryo; H, later gastrula showing the elongation of the invagination (archenteron) and the origin of the mesodermal pouches.

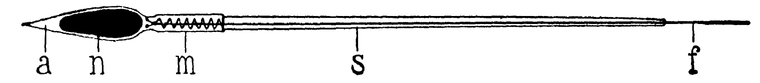


FIG. 157.—Diagram of a sperm cell. a, acrosome; n, nucleus; m, middle piece; s, sheath of flagellum; f, axial filament. (Adapted from Wilson.)

the sperm remains passive as it is drawn into the egg cytoplasm; but in others, the sperm continues lashing its flagellum until the penetration is complete. Simultaneously, the surface membrane—which in the unfertilized egg is called the *vitelline membrane*—lifts off from the egg cytoplasm, forming the *fertilization membrane* (Fig. 85). In most species the fertilization membrane persists, enveloping and protecting the embryo while further development proceeds.

Usually only the head and middle-piece of the sperm enters the egg; and even when the whole sperm becomes engulfed, the flagellum soon disintegrates. The sperm head consists mainly of a nucleus; and this nucleus gives rise to half of the chromosomes in all the cells of the new individual. The middle-piece, at least in many species, contains the centrioles which participate in the cleavage divisions of the egg.

The sperm nucleus swells gradually as it moves toward the center of the egg where it is to join the egg nucleus (Fig. 158). Simultaneously a large single aster forms in the surrounding cytoplasm; and the aster appears to be concerned with bringing the gamete nuclei together. Finally the *gamete nuclei fuse to form the zygote nucleus.* At this stage, the chromosomes of both nuclei are individually visible (Figs. 155 and 158); and it is entirely certain that the chromosomes of the diploid zygote represent a combination of the chromosomes of the haploid gametes. Half the chromosomes of the zygote are derived from the paternal parent, and half from the maternal parent.

Shortly after the zygote nucleus is formed, the egg begins a long series of divisions—giving rise to the many cells of the embryo and adult of the next generation. All these divisions are mitotic, and consequently every cell of the embryo and adult receives a diploid set of chromosomes equally derived from the two parents.

Activation; Parthenogenesis. The sperm performs two functions: (1) it contributes its chromosomes to the zygote nucleus, and (2) it activates the development of the egg. These two functions are separable, to some extent, as is demonstrated by the following experiment. If a sperm be removed just after

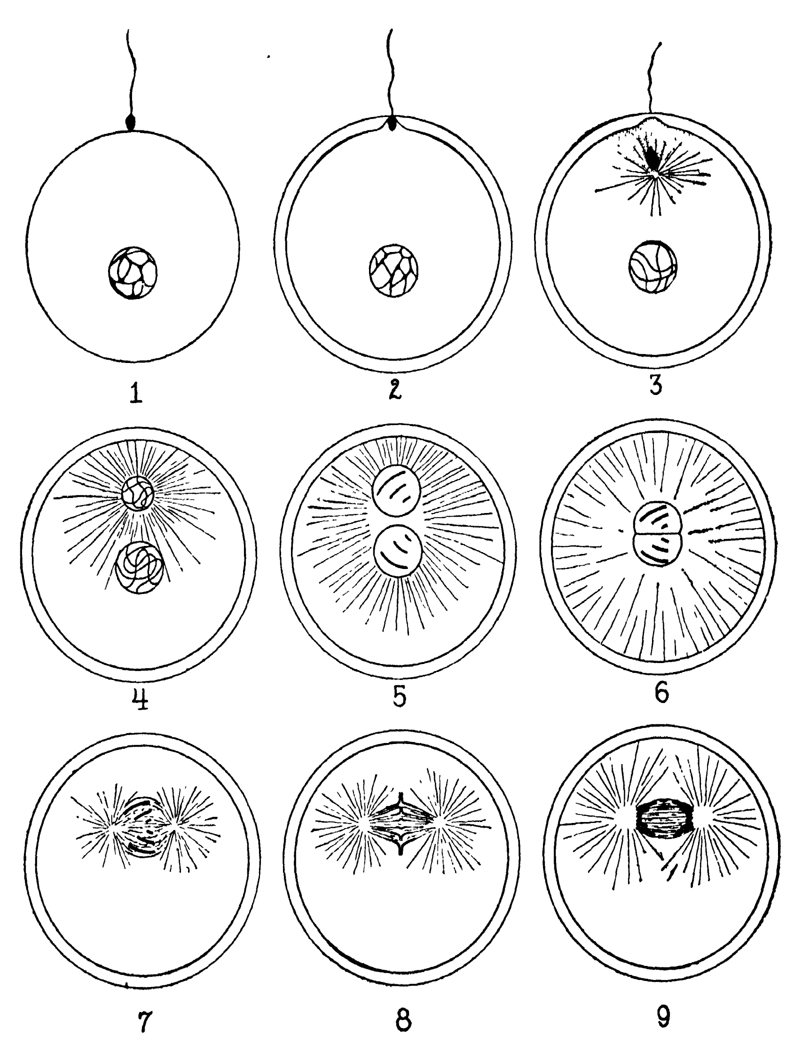


FIG. 158.—Diagram of fertilization. 1, contact of sperm with surface of egg. 2, response of the egg: formation of the entrance cone, which engulfs the sperm, and of the fertilization membrane. 3, sperm head drawn into the egg; appearance of aster. 4, 5, enlargement of sperm nucleus and approach of the two gamete nuclei; appearance of the haploid number of chromosomes (here three) in each gamete nucleus. 6, union of the two gamete nuclei. 7-9, first division of the zygote nucleus, each daughter nucleus receiving one half of each chromosome present in the zygote nucleus.

it has made contact with an egg, fertilization proper (union of the gamete nuclei) cannot occur. Nevertheless such an egg may develop, at least partially, even in the absence of the paternal chromosomes. The contact of the sperm initiates a visible reaction which sweeps over the surface of the egg. This *activation* reaction involves the discharge of a bio-electric current, which precedes the lifting of the fertilization membrane. As a result of activation, the egg becomes non-receptive to other sperm; and the metabolism of the egg is changed and accelerated. In due time the activated unfertilized egg begins to divide; and in some cases it may continue development, forming an embryo, or even an adult—although such individuals are not normal in appearance and vitality.

Activation represents the *response* of an egg to stimulation. In fact a variety of stimuli are now known which can substitute for the contacting sperm. Some eggs can be activated by mechanical pricking, or by drastic temperature changes, or by chemicals, or by sudden changes of the osmotic conditions in the surrounding medium. Apparently the unfertilized egg is all "set" and ready to develop. Normally, the stimulus for starting development is provided by the sperm which first succeeds in contacting the egg surface; but a variety of other strong stimuli may inadvertently "jolt the mechanism" into activity.

The development of an egg, in the absence of fertilization, is called *parthenogenesis*. Parthenogenesis may be artificial, i.e., induced experimentally; or it may be *natural*, in that it occurs normally in the reproduction of some species. An organism produced by artificial parthenogenesis is haploid, at least in the sense that it lacks paternal chromosomes. Moreover, the development of such organisms tends to be abortive. A few animals (e.g., frogs) have been reared into adults by careful nursing; but such adults are small and delicate; and they are never able to reproduce.

Natural parthenogenesis is regularly encountered in certain worms, insects, and crustacea; and may be either haploid or diploid in nature. *Haploid parthenogenesis* is common to the ants, bees and wasps. The *unfertilized* eggs of these animals

always develop into *males*, which, being haploid, produce sperm, not in the usual fashion, but by *mitosis*. The fertilized eggs of these species always develop into *females*, and these diploid females finally produce haploid eggs by meiosis, as in other animals.

Diploid parthenogenesis is exemplified by the aphids, or plant lice. Commonly the female aphid produces diploid reproductive cells by *mitosis*. These diploid cells are called *parthenogonidia*, rather than eggs. During the spring and summer months, the parthenogonidia develop into other parthenogenetic females; and in this way a number of asexual generations may be produced. In the fall, however, the parthenogonidia develop into *males* and *sexual females*; and these forms of the organism produce haploid gametes, by meiosis, in the usual fashion. Then further development cannot occur until fertilization takes place. If aphids are raised in a greenhouse, under uniform conditions throughout the year, the sexual generation may never appear; and in certain species, males are unknown even under natural conditions. Thus parthenogenesis, although technically an asexual process, bears a very close relationship to the sexual modes of reproduction.

Development: The Embryonic Period. During development, the fertilized egg undergoes many changes. The original cell multiplies; and the many resulting cells differentiate—forming the tissues and organs of the growing body. Collectively these complex transformations make up development. Until the time of hatching, or birth—i.e., until the offspring emerges from the egg or from the uterus—the developing individual is called an *embryo*. In *detail*, embryonic development varies widely in different species; but certain broad fundamental resemblances can be observed in the *early* development of practically all multicellular animals.

Cleavage—Formation of the Blastula. Soon after fertilization the zygote divides by repeated mitosis, forming a group of smaller cells. These early divisions, which lead to the formation of a multicellular embryo, are referred to collectively as *cleavage*.

Homolecithal eggs (Fig. 154, A), which display a homogenous cytoplasm and relatively little yolk, nevertheless possess a distinct *polarity*. The animal pole is marked by the point where the *polar bodies* were formed (Fig. 156, A); and the opposite pole is referred to as the *vegetal pole*. The first and second cleavages pass through the poles, giving rise to a four-celled embryo (Fig. 156, D). The third cleavage passes at right angles to the first two, at or near the equator; and now the embryo consists of eight fairly equal-sized cells—four in the animal hemisphere and four in the vegetal hemisphere. The further cleavages are usually quite synchronous so that the number of cells increases in geometrical progression—8, 16, 32, 64, etc. When several hundred cells are formed, the embryo typically has the form of a hollow sphere. This is the *blastula* stage; and the cavity within the blastula is called the blastocoel (Fig. 156, F).

Telolecithal eggs (Fig. 154, B) have an abundance of yolk, especially in the vegetal hemisphere; and the cleavage divisions of the telolecithal egg are not equal. The first *horizontal* cleavage passes above the equator; and consequently the cells in the animal hemisphere are distinctly smaller than those in the vegetal region. The lower cells contain a larger amount of yolk and divide less rapidly than the upper cells. Accordingly, when the blastula is formed, the cells in the vegetal hemisphere are larger and less numerous (Fig. 159, B). Also the blastocoel is small and lies eccentrically, nearer the animal pole (Fig. 159, B). In very heavily yolked eggs, such as the eggs of birds and reptiles, the vegetal cytoplasm may not cleave at all; and in such cases the blastula consists of a small disc of cells, roofing over a narrow blastocoel, in the region of the animal pole (Fig. 159, C).

Gastrulation—Formation of Endoderm. A few simple colonial organisms do not progress beyond the blastula stage. In Volvox (Fig. 42, E), for example, the adult colony consists merely of a hollow sphere of cells, among which very little differentiation has occurred.

But in higher animals, as cleavage continues, the cells in the vegetal region appear to be crowded inward, so that they en-

croach upon the blastocoel (Fig. 156, G). This inpocketing, or *invagination*, continues until a tubular pouch, the *archenteron*, is formed (Fig. 156, H). The archenteron is the embryonic forerunner of the *digestive tract*. The cells forming the wall of the archenteron are specified as the *endoderm;* and the cells remaining at the surface of the embryo are called the *ectoderm*. Moreover, such a two-layered embryo is a *gastrula;* and the orifice leading into the archenteron is the *blastopore*.

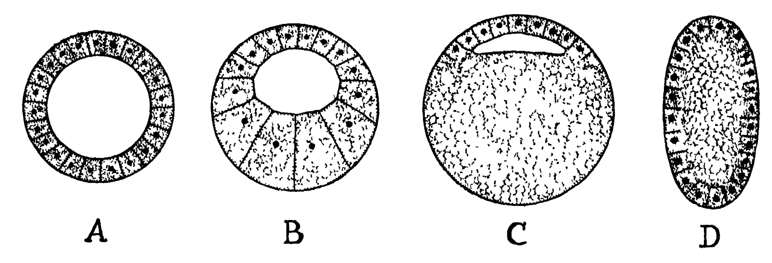


FIG. 159.—Several types of blastulae: A, from homolecithal egg; B, from moderately telolecithal egg; C, from extreme telolecithal egg; D, from centrolecithal egg.

In heavily yolked eggs *gastrulation* is modified considerably (Fig. 160, A-B); but it is always possible to recognize a gastrula. This two-layered embryo possesses a saccular archenteron, which communicates with the exterior through a blastopore.

The Mesoderm and the Coelom. Very primitive animals, such as Hydra and other Coelenterates (p. 352), do not progress further than the gastrula stage. The adult body of such animals is two-layered, consisting entirely of ectoderm and endoderm. In all higher animals, however, a third layer of cells, the *mesoderm*, is formed between the ectoderm and endoderm. These three embryonic layers—the *ectoderm*, *endoderm* and *mesoderm*—are called the *primary germ layers* of the embryo. The ectoderm is destined to give rise to all epithelial layers on the external surface of the body, and also to the sensory and nervous tissues of the animal. The endoderm provides a glandular *lining* throughout the *digestive tract* and all of its branches; and the mesoderm gives rise to all other body structures—such as the muscle, bone, and connective tissues of the animal. Ani-

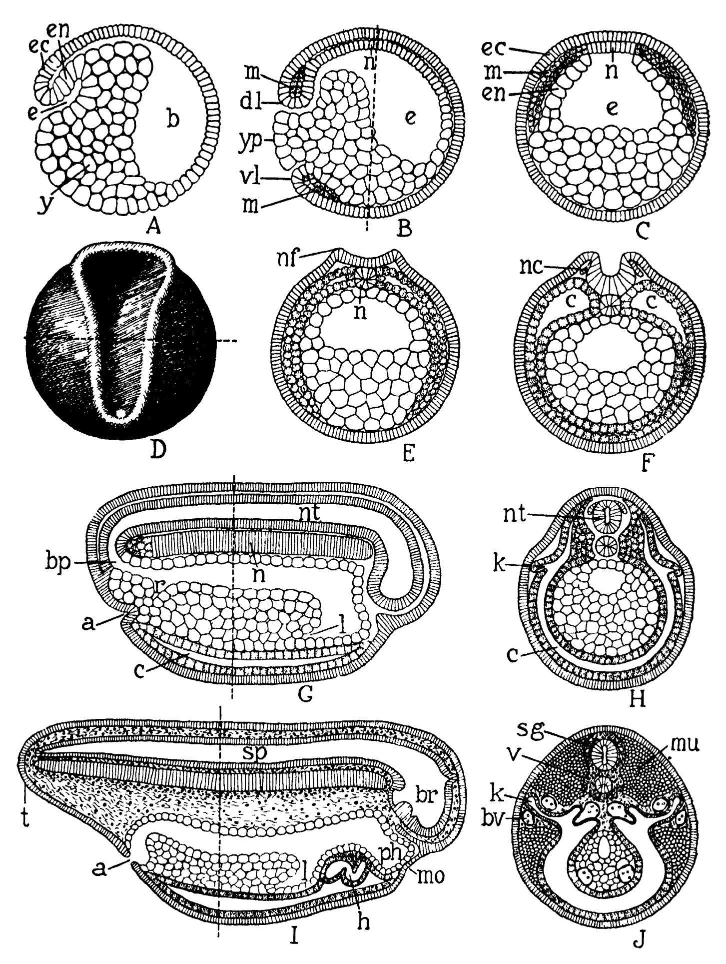


FIG. 160.—Amphibian embryos, showing development of typical vertebrate structures. A, median longitudinal section of early gastrula; B, similar section of late gastrula; C, cross-section of same stage; D, dorsal view of slightly later stage, showing neural folds; E, cross-section of same stage; F, similar section of later stage; G, median longitudinal section of embryo after closing of neural tube; H, cross-section of same stage; I, longitudinal section of embryo at time of hatching; J, cross-section of same stage. ec, ectoderm; en, endoderm; y, yolk cells; b, blastocoel; e, enteron; m, mesoderm; dl, dorsal lip of blastopore; vl, ventral lip of blastopore; yp, yolk plug; n, notochord; nf, neural fold; nc, neural crest (which develops into sensory ganglia); c, coelom; nt, neural tube; bp, blastopore; a, anus; r, rectum; l, liver; k, embryonic kidney tubule; br, brain; sp, spinal cord; t, tail; h, heart; ph, pharynx; mo, mouth; mu, muscle; sg, sensory ganglion; v, vertebra; bv, blood vessel.

mals possessing only ectoderm and endoderm are said to be *diploblastic;* whereas those having all three germ layers are said to be *triploblastic.*

The mesoderm arises differently in different embryos. In the earthworm and many other invertebrates, the mesoderm derives chiefly from a pair of large cells, the *pole cells,* which are pushed into the blastocoel at or about the time of gastrulation (Fig. 161, 1). These mesoderm cells multiply rapidly, forming two strands of tissue which crowd forward on either side of the archenteron, between the ectoderm and endoderm (Fig. 160, 3). As the mesoderm proliferates, it tends to fill and obliterate the blastocoel, encroaching above and below the archenteron (Fig. 160, 3). Then a new cavity develops in the mesoderm itself; and this *coelom,* or *body cavity,* is found in all higher animals. The coelom enlarges and encircles the archenteron completely, separating the mesoderm into two distinct layers (Fig. 160, 4). The outer layer, or *somatic mesoderm,* together with the ectoderm around it, becomes the *body wall* of the adult; and the inner layer, or *visceral mesoderm,* together with the endoderm, becomes the *gut wall* of the adult.

All triploblastic animals except the flatworms, possess a coelom, although the coelom does not always arise in the same manner. The coelom surrounds the digestive tract and separates it from the body wall. This arrangement permits the digestive tract to move freely—independent of the movement of the body as a whole. Generally the archenteron continues to invaginate, until it establishes communication with the exterior at the opposite end of the embryo. In this way the digestive tract becomes a tubular passage, leading from the *mouth* to the *anus.* Accordingly, the body structure of most higher animals can be described as that of a "tube within a tube." The inner tube, which is the enteron, or digestive tract, is separated from the outer tube, or *body wall,* by the *coelom,* which extends throughout most of the length of the body.

In many invertebrates, such as starfish and other Echinoderms (p. 742), the mesoderm and coelom arise from a pair of hollow evaginations, the *enterocoelic pouches* (Fig. 156, H). These

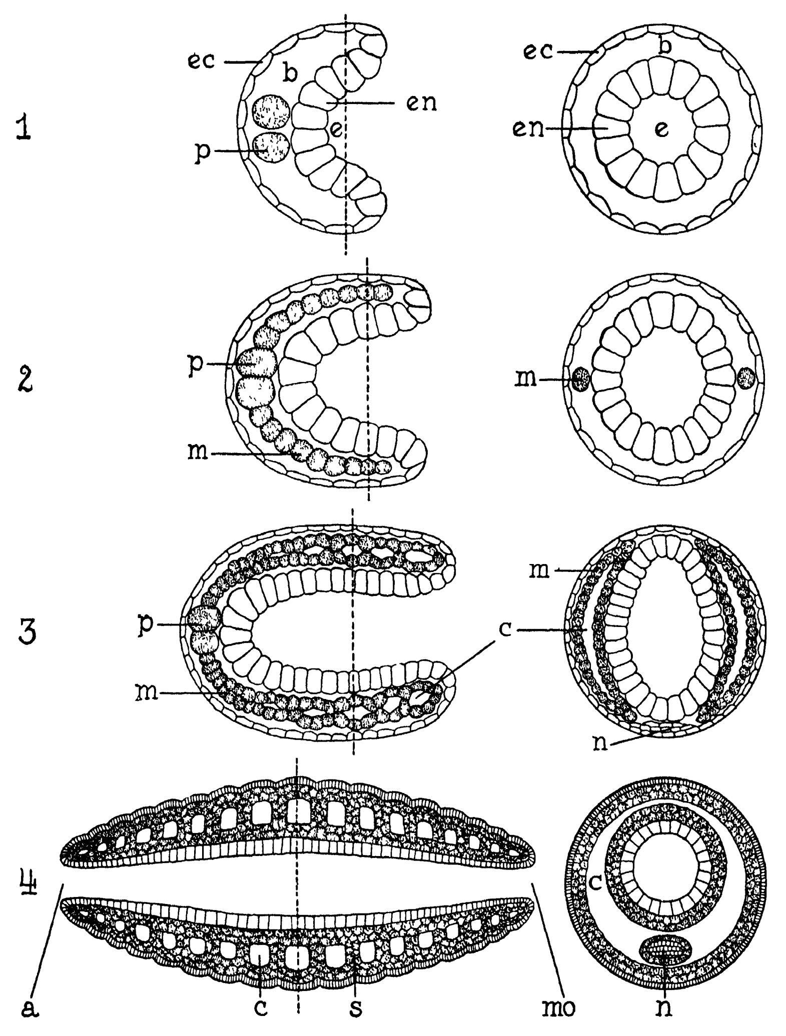


FIG. 161.—Development in the earthworm. Figures on the left represent horizontal longitudinal sections, those on the right cross-sections through the points indicated by the dotted lines. 1, gastrula; 2, formation of mesoderm from the pole cells; 3, formation of coelomic cavities and origin of the nerve cord from the ectoderm; 4, the general form and structure of the body established; the nerve cord has become separated from the ectoderm by the mesoderm. ec, ectoderm; en, endoderm; p, pole cell; b, blastocoel; e, enteron; m, mesoderm; c, coelom; n, nerve cord; a, anus; mo, mouth; s, septum. (Adapted, in part, from Sedgwick and Wilson.)

outpocketings pinch off from the archenteron and grow larger until they obliterate the blastocoel. Meanwhile the cavity of each pouch encircles the enteron, forming the definitive coelom.

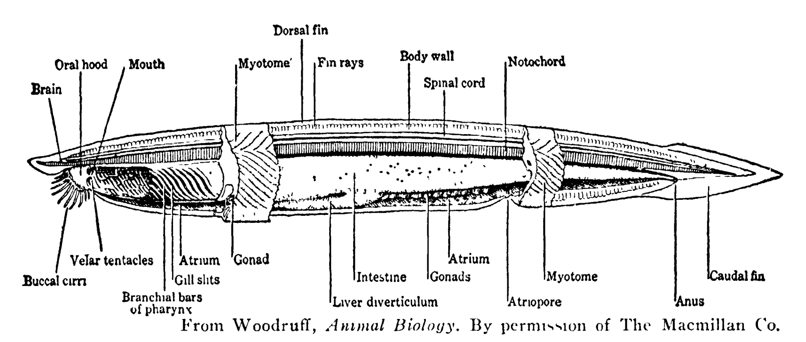
A similar method of mesoderm formation is also found in Amphioxus (p. 332) and some other primitive chordates (p. 332); but the mesoderm arises in a different way, in embryos of true vertebrates. In the frog, for example, most of the mesoderm is formed by a proliferation of the cells of the *rim of the blastopore*, i.e., at the junction between the ectoderm and endoderm (Fig. 160, B-C). However, some mesoderm seems to bud off from the sides of the archenteron.

Regardless of origin, the mesoderm grows, crowding forward in the embryo and insinuating itself between the ectoderm and endoderm along both sides of the archenteron. Then the *coelomic* cavity appears (Fig. 160, E) and enlarges (Fig. 160, F), finally encircling (Fig. 160, H) the enteron. Thus the coelom comes to separate the *visceral and somatic layers* of the mesoderm; and the body wall becomes differentiated from the gut wall. In the *dorsal* region, however, the opposite parts of the developing coelom fail to meet each other above the enteron, although ventrally the coelom completely encircles the gut (Fig. 160, J). Owing to this failure of the coelom to encircle the gut in the dorsal region of the vertebrate embryo, the gut wall remains in continuity with the body wall—by way of a sheetlike connection of mesoderm tissue (Fig. 160, J). This connecting sheet of mesoderm besomes the *mesentery*, which suspends the digestive tract in the coelomic cavity of the adult. Also the mesentery provides a connection through which nerves and blood vessels pass between the body wall and the gut wall, which otherwise are isolated throughout the length of the body.

Further Development; Vertebrate Animals. All vertebrates (Fish, Amphibians, Reptiles, Birds and Mammals) resemble each other as to many characteristics of development and structure (p. 743); but *three* vertebrate characteristics are of primary importance. All vertebrates possess: (1) a *segmented vertebral column* (also called the "backbone"); (2) a *dorsally placed tubular nervous system* (i.e., a tubular brain and spinal

cord which are enveloped by the vertebral column); and (3) *gill clefts* (several, usually five, pairs of slitlike channels, leading from the digestive tract to the exterior, in the region of the pharynx).

Among the fish, the gill arches bear functional gills, which serve as respiratory organs. But in higher vertebrates, including man, the gill clefts appear only transiently during embryonic



From Woodruff, *Animal Biology*. By permission of The Macmillan Co.

FIG. 162.—Amphioxus, one of the primitive chordates. Note especially: 1, the notochord; 2, the *dorsal* nervous system (brain and spinal cord); and 3, the gill slits.

development—although modified remnants of the gill slits persist in the adult body (p. 336).

Despite the large number of species, vertebrates are classified as a sub-phylum in the *phylum Chordata* (p. 743). In addition to the vertebrates, the phylum Chordata includes a number of less familiar animals, which possess gill clefts and a dorsal hollow nerve cord, *but no true vertebral column.* In place of a vertebral column, primitive chordates possess an unsegmented flexible rodlike supporting structure, the *notochord,* which occupies an equivalent position in the body (Fig. 162). Vertebrate animals develop a notochord, but only transiently, during the embryonic period, prior to the appearance of the segmented vertebral column. In fact it is the possession of a notochord, as well as of gill clefts and a dorsal nervous system, which clinches the relationship between the vertebrates and more primitive chordate forms, and justifies placing all these animals in the same phylum.

Origin of the Nerve Cord and Notochord. The nerve cord and notochord arise almost simultaneously, in the late gastrula period (Fig. 163, a-c). The nerve cord comes from ectoderm, as will be described presently; whereas the notochord, at least in some forms, arises from a strand of endoderm, which buds off from the archenteron (Fig. 163, b).

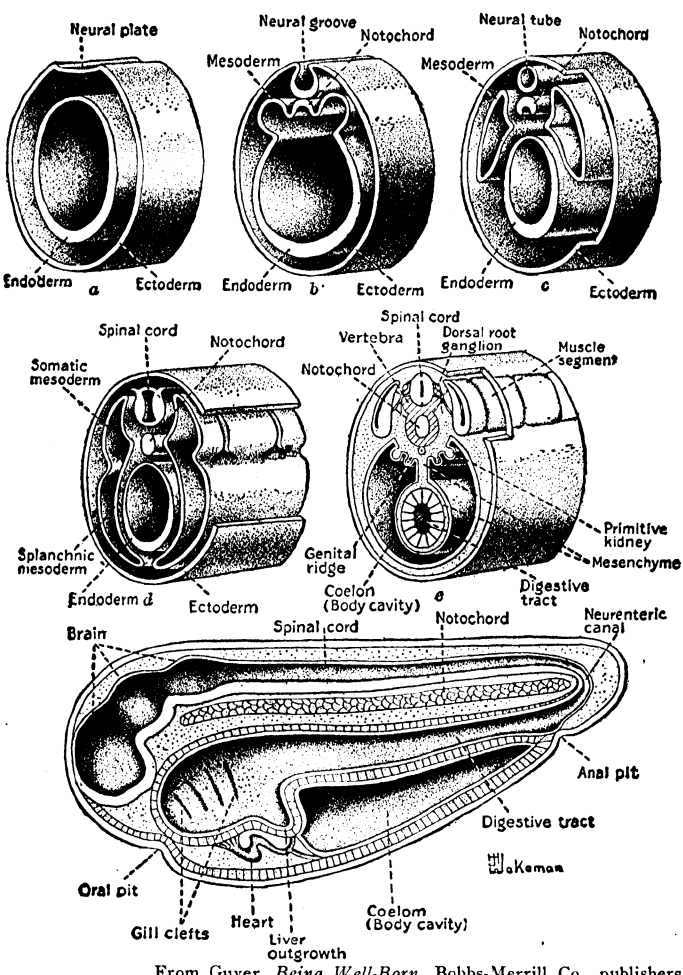
The nerve cord first appears on the dorsal surface of the gastrula. In the beginning it is merely a shallow depression, called the *neural groove* (Fig. 163, b), which runs lengthwise of the embryo, and is broader at the anterior end (Fig. 160, D). The neural groove is bounded laterally by the *neural folds,* which rise slightly from the surface of the embryo. Posteriorly the neural folds approach the *blastopore* (Fig. 160, D), which is called the *yolk plug* because it is blocked by yolk cells.

As development proceeds, the neural groove sinks below the surface of the embryo, and the neural folds come together along the mid-dorsal line (Fig. 163, b-c). This invagination forms the *neural tube,* which will give rise to the brain and spinal cord (Fig. 163, f). The neural tube continues to sink below the surface of the embryo; and soon it becomes roofed over by surface ectoderm, which encroaches from the sides. At an early stage (Fig. 160, G), the cavity within the neural tube establishes continuity with the enteron cavity, although later, this communication becomes obliterated and the enteron breaks through more ventrally to join an invagination from the exterior, forming a new opening, the *anus* (Fig. 160, I).

The *neural tube* gives rise to: (1) the entire *nervous system,* including the brain, spinal cord, and nerves; and (2) the special *sensory epithelia,* such as the retina of the eye. The *brain* develops from the anterior portion of the neural tube (Fig. 163, f). This anterior part is larger initially and grows faster than the long narrow posterior portion, which becomes the *spinal cord.* The nerves of the body represent outgrowths from the neural tube. Each nerve consists of a bundle of fibers which originate from nerve cells as soon as these begin to differentiate in the developing brain and spinal cord.

The flexible unsegmented *notochord* is a skeletal rod which

is found in all vertebrate embryos, extending lengthwise through the embryo—between the neural tube and the archen-



From Guyer, *Being Well-Born,* Bobbs-Merrill Co., publishers

FIG. 163.—Diagrams representing stages in the development of a vertebrate: a to e indicate sections cut from the mid-body region of the developing embryo; f, represents the embryo cut in half to show inside view.

teron (Fig. 163, d-f). In vertebrates, however, the notochord is a short-lived, vestigial structure. In most cases it is totally replaced by the segmented vertebral column; but among primi-

tive vertebrates (e.g., lampreys, sharks and frogs), remnants of the notochord can be found between the vertebrae, even in the adult animals (p. 743).

Origin of the Skeleton and Musculature. Except for certain parts of the skull—which arise from the ectoderm overlying the developing brain—the *skeleton* arises from mesoderm. Initially the skeletal material is *cartilage;* but this cartilage tissue (p. 344) is almost completely replaced by bone during later embryonic development—except in some of the lower fishes (p. 743). However, the form and pattern of the skeletal parts remain essentially the same during the period when the cartilage is resorbed and replaced by bone.

In vertebrate embryos (at the stage shown in Fig. 163, d and e) one can identify a *dorsal mass* of mesoderm, which lies on either side of the notochord and neural tube. As development proceeds, this dorsal mass becomes subdivided by a number of transverse creases into a series of blocklike segments, called *somites.* The mesodermal somites (Fig. 163, d) give rise to the skeletal and muscular structures in the several segments of the body. Each vertebra is blocked off by the mesoderm surrounding the notochord and neural tube, as this tissue differentiates into cartilage. The cartilage grows dorsally around the neural tube, forming a *neural arch* (Fig. 163, e); and ventrally, the cartilage first surrounds (Fig. 163, e), and then *invades* the notochord. Gradually all the notochordal tissue is resorbed, leaving the segments of cartilage, which become the *centra* of the vertebrae. Accordingly, the vertebral column is made up of a series of segments, or *vertebrae,* linked together end to end. Collectively the vertebrae form a flexible skeleton—the vertebral column—which lies embedded in the dorsal body wall. The neural arch of each vertebra surrounds one portion of the spinal cord, so that the column as a whole provides a protective tunnel, which houses the spinal cord throughout its length. This protective housing becomes even more effective when the cartilage is later replaced by bone (in all except the lower vertebrates).

Virtually all the muscle in each body segment arises from the

lateral part of the mesodermal somites. Some of these mesoderm cells remain in situ, giving rise to the massive muscles of the back; but others migrate ventrally—through the mesentery into the gut wall—and into the lateral and ventral parts of the body wall. In the gut wall this mesoderm differentiates into *visceral* (non-striated) *muscle* (p. 340); but in the body wall it gives rise to *skeletal* (striated) muscle (p. 340). Most of the *connective tissues* (p. 344) also arise from cells which migrate out from the mesodermal somites.

Further Development of the Digestive Tract and its Outgrowths. The *mouth*, in vertebrates, arises as a shallow invagination, the *oral pit*, which pushes inward and joins the archenteron near the anterior extremity of the embryo (Fig. 163, f); and the *anus* arises similarly at the posterior end of the enteron, just ventral to the blastopore. Thus part of the lining of both the mouth and the anus is derived from ectoderm; and both these passages display a line of junction between the ectodermal and endodermal tissues. Among invertebrates, the blastopore persists, becoming the mouth, as in the earthworm (Fig. 161, 4).

The *gill slits* originate as a series of outpocketings (Fig. 163, f), which push laterally from the endoderm to join a corresponding set of inpocketing from the surface ectoderm. In higher vertebrates the penetration of the gill passages is usually incomplete—although one pair of clefts forms a passage which persists and gives rise to the *Eustachian tubes* (p. 368) and *middle ear chambers* of the adult.

The *lungs*, *liver*, *pancreas* and *urinary bladder* all originate as tubular *outgrowths from the developing enteron*. Accordingly all these structures possess an *internal lining* derived from endoderm. However, visceral mesoderm is always present in these outgrowths at the time when they originate from the enteron; and this mesoderm gives rise to the muscle, connective tissue, blood and lymph vessels, and the *external* epithelia of all the organs which grow out from the gut. In fact the endoderm provides only the internal epithelium of the digestive tract and its branches. This epithelium is particularly important in

the case of the liver, pancreas, and other digestive glands, because only these endoderm cells are destined to participate in the production of digestive juices.

Origin of Other Structures. The blood vessels, including the *heart* (see p. 404), and the *lymph vessels*, originate as fissures, or sinuses, in the mesoderm, which eventually become interconnected into a continuous system of vessels. In the early embryo the *blood corpuscles* develop from cells in the sinus walls; but later they are generated by special tissues, such as *bone marrow* (p. 400). The *kidneys* and excretory ducts—and the *gonads* (ovaries or testes) and gonoducts—originate from mesodermal foldings, in the dorsal wall of the coelom, on either side of the mesentery (Fig. 163, e).

Contributions of the Primary Germ Layers. In summary, the eventual contribution of each germ layer, especially in vertebrate animals, can be given as follows:

The *ectoderm* gives rise to: (1) the entire nervous system—including the brain, spinal cord, ganglia, nerves, and the receptor cells of the sense organs; (2) the outer, or *epidermal layers* of the skin, and skin structures—including hair, nails, the superficial parts of scales and feathers, and the secretory cells of skin glands (e.g., sweat glands); (3) the lens of the eye; and (4) most of the *lining* of the mouth, nostrils and anus, including the enamel layer of the *teeth*.

The *endoderm* provides the *lining* of the enteron (excluding part of the mouth and anus) and all its off-shoots. These off-shoots include not only the digestive glands such as the liver and pancreas; but also the lungs and other parts of the respiratory tract; the thyroid and thymus glands; and most of the urinary bladder and the urethra (p. 475).

Finally, the *mesoderm* gives rise to all other body structures. These include (1) the deeper (dermal) layers of the skin and associated structures; (2) the gut wall, except for its endodermal lining; (3) the mesenteries and other parts of the epithelial lining of the coelom and its derivatives; (4) the kidneys and most of the reproductive system; (5) the vascular system, including the heart, blood vessels and lymphatics; (6) the mus-

cles; and (7) the various connective and supporting tissues, including almost all the bones, and the deeper (dentine) layers of the teeth.

Histology: Origin and Nature of the Body Tissues. All the cells of the developing embryo possess equivalent chromosomes, derived by mitosis from the zygote; and in young embryos, the cells display little or no obvious differentiation. But sooner or later the cells in different regions of the embryo become different: some become muscle, some nerve, etc., until finally all the *tissues* of the adult become recognizable.

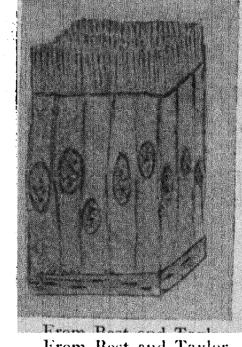
Initially the particular destiny of an embryonic cell is not determined, and many factors, both physical and chemical, cooperate in determining the eventual fate. In the frog embryo, for example, the ectoderm cells which lie in the *mid-dorsal* region of the embryo would normally give rise to nerve cells. But these same cells can be transplanted to the side of another embryo—and in this case they become skin cells. In other words, the cells develop differently according to their respective positions in the embryonic body. The physical and chemical forces which act upon the surface cells of an embryo differ from those that play upon the deeper cells; and there are many less obvious differences which affect development in the different embryonic regions. Moreover, cells which have become differentiated sometimes exert a differentiating influence upon other cells, especially in nearby regions of the embryo (p. 676). But the problems of differentiation will be considered later (Chap. 25); and at present we will be concerned only with the end results of differentiation—the *tissues of the adult animal.*

Many *specific* differences are found among the tissues of various animals, although the same four general types can always be recognized. These *fundamental tissues* are: (1) *epithelium,* (2) *muscle,* (3) *nerve* and (4) *sustentive* (*connective*) *tissue.* Each of these fundamental tissues will be described in terms of the vertebrate animal.

Epithelial Tissues. The epithelial tissues, which cover the various external and internal *surfaces* of the body, are com-

posed of closely fitting cells, with only a minimum of intercellular material binding the tissue into a continuous membrane.

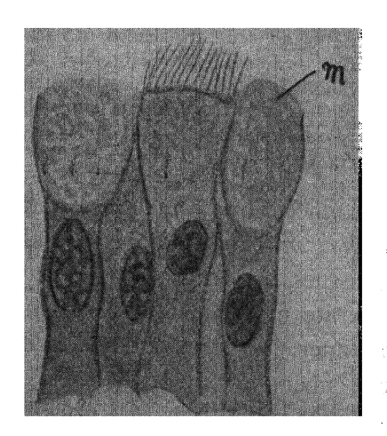
Epithelial cells are variously modified at different surfaces; and accordingly, several kinds of epithelia can be recognized. In *squamous* epithelium (Fig. 14, 3) the cells are flat and scalelike; whereas in *columnar* epithelium the cells are cylinders, or bricks, of greater or lesser depth (Fig. 14, 1-2). In *simple* epithelia there is only a single tier of cells, but in *stratified* epithelia there are several, or many tiers. Moreover, some epithelia are *ciliated* (Fig. 164), but others are *non-ciliated.*



From Best and Taylor, *The Living Body*

FIG. 164.—Ciliated epithelium.

Some epithelia are composed entirely of *glandular cells,* which secrete their products at the epithelial surface. This is true of the lining of the coelomic cavity and all of its derivatives. In the abdominal cavity, where the epithelium is called the *peritoneum;* in the thoracic cavity, where it is called the *pleura;* and in the pericardial cavity, where it is called the *pericardium*—all the cells produce a watery, or *serous,* fluid, which lubricates the internal surfaces of the body. But in the *mucosa,* which lines the digestive tract, only some of the cells are gland cells (Fig. 165). All multicellular glands in the body are derived from epithelial outpocketings (Fig. 166). Some multicellular glands are *simple glands,* like the gastric glands of the stomach, being composed of epithelial cells (Fig. 166, C); but others are *compound glands* (Fig. 166, E), which contain



From Best and Taylor, *The Living Body*

FIG. 165.—Goblet cells from mucosa of the trachea. m, mucus.

a significant amount of connective tissue between the epithelial channels. Likewise compound glands are independently supplied with nerves and blood vessels; and each is covered by an epithelial membrane.

Muscle Tissues. The three kinds of muscle tissue of vertebrate animals are: (1) *visceral muscle*, which is found in most of the internal organs, or *viscera;* (2) *skeletal muscle*, which

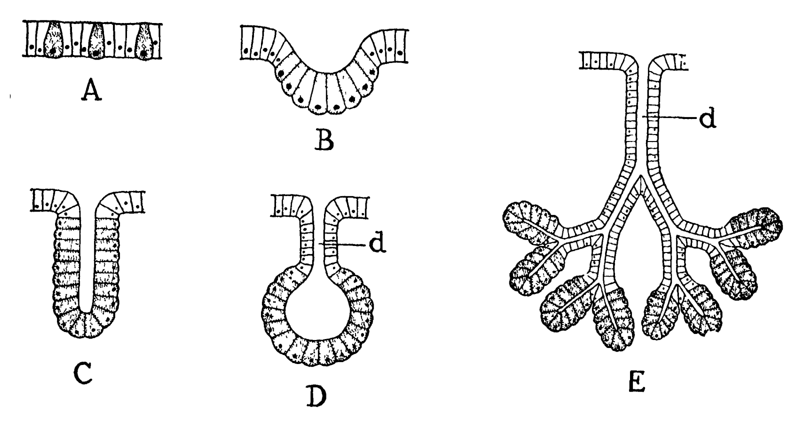


FIG. 166.—Structure of glands; the actual gland cells are shaded in each figure. A, single gland cells scattered among ordinary epithelial cells; B, simple multicellular gland, consisting of a group of gland cells lining a slight invagination of the epithelium; C, simple tubular gland; D, simple alveolar gland; E, compound tubular gland (large glands, such as the liver and pancreas, are of this type, with thousands of secreting alveoli). d, duct.

occurs mainly in the body wall, connected to the bones and other skeletal parts; and (3) *cardiac muscle*, which is found only in the heart. All muscle tissues are characterized by *elongate* cells or fibers, which generate movement by shortening, or contracting, in a forcible manner. No force is developed during the *relaxation* of a muscle fiber—or, in other words, muscle fibers work, not by pushing, but by pulling. All muscle tissues appear to generate a contractile force by the shortening of numerous delicate protoplasmic fibrils, the *myofibrillae*, which are present in the fibers. The myofibrils run lengthwise through the fluid protoplasm, or *sarcoplasm*, of the fibers, as can be demonstrated by proper staining, in all varieties of muscle tissue.

In *visceral muscle*, each fiber is a single spindle-shaped cell (Fig. 167, A); but the individual fibers of *skeletal muscle* are syncytia, containing many nuclei (Fig. 167, B). In skeletal muscle, the nuclei are found at regular intervals near the sur-

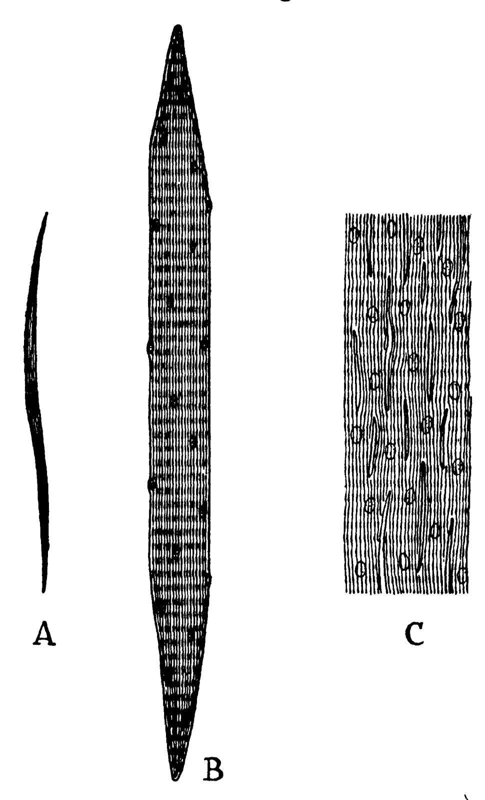


FIG. 167.—The three kinds of muscle tissue. A, a visceral muscle cell; B, a single skeletal muscle fiber; C, a small piece of cardiac muscle tissue.

face of the fiber, just subjacent to a well-marked membrane, the *sarcolemma*. In skeletal and cardiac muscle, but not in visceral muscle, one can see a number of transverse striations (Fig. 167, B and C). These striations look like a series of parallel bands, passing across the fibers—but they are not actual partitions subdividing the fiber into discrete sections. Probably the striated appearance is due to a pattern of evenly disposed markings on the myofibrillae.

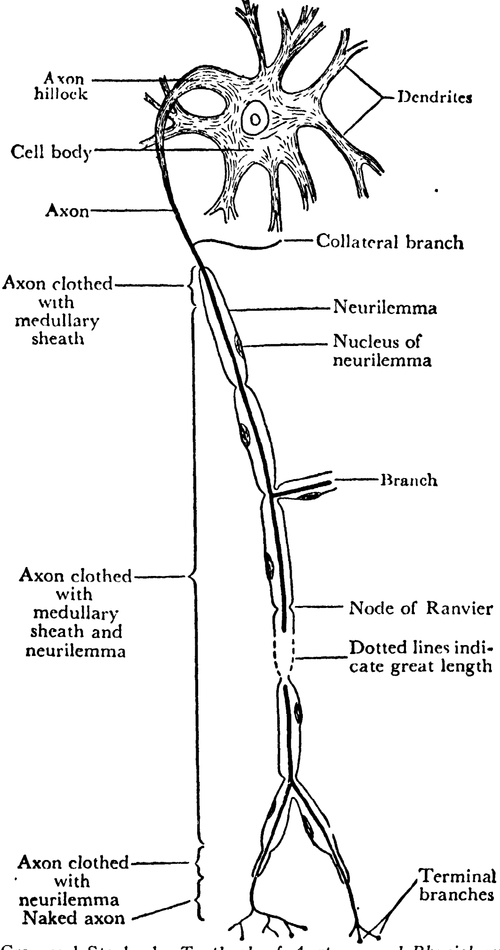
Cardiac muscle is found only in the vertebrate heart. The general structure of the tissue is like that of skeletal muscle, except that cardiac fibers interconnect with one another, so that the heart as a whole represents a huge syncytium (Fig. 167, C). Cardiac myofibrils resemble those of skeletal muscle, giving a similar cross-striated appearance to the tissue. However, in cardiac muscle the nuclei do not lie near the surface of the fibers, as in skeletal muscle, but are deeply placed, as in visceral muscle.

Functionally the three types of muscle are also quite different. The action of skeletal muscle is very rapid—such that contraction and relaxation are completed in less than 0.1 second—compared to an average of 1 and 10 seconds, respectively, for cardiac and visceral muscles. Also the contractions of skeletal muscle are finely graded and precisely controlled as to their force and amplitude. Essentially each separate skeletal muscle is a bundle containing thousands of parallel fibers, stretching between two parts of the skeleton. Each fiber receives an individual nerve supply. Accordingly the demands of the nervous system can be varied in such a way that all or only some of the fibers contract, adding their strength to the whole contraction. Cardiac muscle, in contrast, tends to contract in an *all-or-none* fashion; and a single excitation tends to spread throughout the whole syncytium. In lesser degree such generalized contractions also occur in visceral muscle; but in this tissue the excitation seems to pass from cell to cell.

Nerve Tissue. The cells of the nervous system are called *neurons* (Fig. 168). Each neuron consists of a cell body, or *centron*, i.e., the nucleus and the cytoplasm immediately surrounding the nucleus—and of delicate threadlike *nerve fibers*, which extend out from the cell body. Some of these fibers normally conduct impulses toward the centron, and these fibers are called *dendrons;* but other fibers, the *axons*, normally convey impulses away from the centron. The many neurons which compose the nervous system form a co-ordinating system of fibers connecting the many sensory and motor structures of the body.

The centron part of a nerve cell maintains the nutrition of its own outlying fibers. Thus an axon or dendron which is cut

off from continuity with its centron undergoes degeneration, although a replacement of the fiber may be effected by a new



From Kimber, Gray and Stackpole, *Textbook of Anatomy and Physiology*. By permission of The Macmillan Co., publishers

FIG. 168.—A neuron.

outgrowth from the cut end. The centrons of the nervous system are aggregated in small masses, called *ganglia*, and—to a much greater extent—in the brain and spinal cord. *Nerves*—which lead to and away from the ganglia, brain, and spinal cord

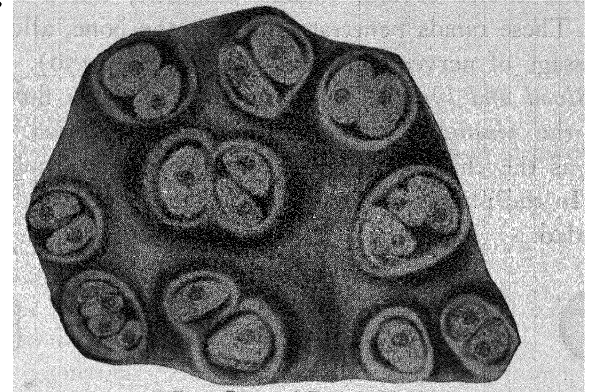
—are made up entirely of axons, dendrons, or both, running together in a common sheath. In many nerves, each fiber is insulated from its neighbors by an individual sheath (Fig. 168) of fatty material, which is called the *myelin* or *medullary sheath*. However, some nerves, particularly in the autonomic system (p. 603), are *non-myelinated*.

Connective (Sustentive) Tissues. The connective tissues bind the other tissues together, giving substantial form to each organ, and connecting and supporting the various organs. In all connective tissues, the *intercellular matrix* is far more conspicuous than the cells by which this matrix is secreted. In fact the character of the matrix mainly determines the properties of the particular kind of connective tissue in question—as may be noted in the following description.

1. *Fibrillar connective tissues*. The matrix of the fibrillar tissues is characterized by the presence of numerous non-living fibers, which form dense, interlacing networks, or thick parallel strands. The *fibroblasts*, or cells which form the matrix, are usually difficult to see among the fibers. They are inconspicuous amoeboid cells, capable of migrating to the various parts of the tissue. The chemical nature of the fibers differs in different connective tissues. In general, two main types are recognized: (a) *white fibers*, which are relatively delicate and inelastic, and (b) *yellow fibers*, which are stouter and more elastic. White fibrous connective tissue is widely distributed throughout the body; but the yellow type of connective tissue is encountered mainly in tendons, which fasten the muscles to the bones; and in *ligaments*, which form the joints between the bones.

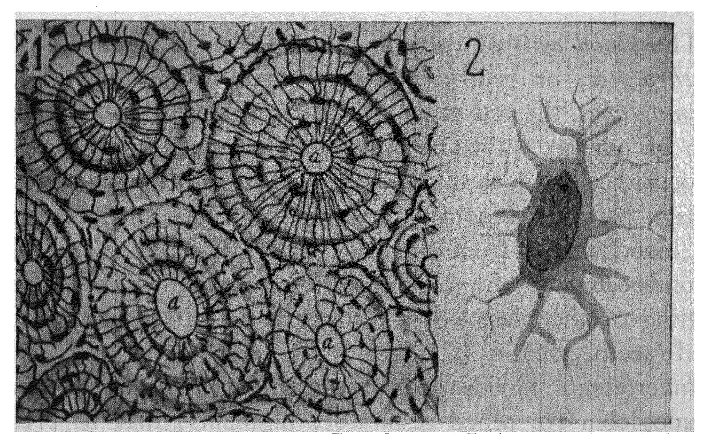
2. *Cartilage* (Fig. 169). The matrix of cartilage is composed mainly of a protein substance, *chondrin*. The chondrin appears as a homogeneous mass between the cells, or *chondroblasts*, which secrete it. Cartilage has a flexible resilient consistency. In lower vertebrates cartilage forms the entire skeleton, but in higher vertebrates, cartilage supplements bone, i.e., cartilage is used as a padding between the bones, and as the skeleton of parts of the body, such as the nose and ears, where flexibility is a

desirable characteristic. Some kinds of cartilage display fibers, like those of fibrillar connective tissue, imbedded in the chondrin matrix.



From Best and Taylor, *The Living Body*.
After Maximow, and Krause

FIG. 169.—Hyaline cartilage. One to several cartilage-producing cells (chondroblasts) occupy each of the spaces (lacunae) in the chondrin matrix.



From Best and Taylor, *The Living Body*

FIG. 170.—Compact bone. 1, cross-section showing Haversian canals (a) with concentric lamellae; 2, enlarged drawing of a bone-forming cell (osteoblast).

3. *Bone* (Fig. 170). Bone is the characteristic skeletal material of most vertebrate animals. The matrix of bone is hard and rigid, being composed largely of phosphate and carbonate compounds of calcium. The bone cells, or *osteoblasts*, which deposit

the bony matrix, are small cells with numerous fine cytoplasmic branches (Fig. 170, 2). Usually the osteoblasts are arranged in concentric circles around tubular channels, called *Haversian canals*. These canals penetrate through the bone, allowing for the passage of nerves and blood vessels (Fig. 170).

4. *Blood and lymph.* Blood (Fig. 171) has a fluid matrix, called the *plasma*. This complex aqueous solution (p. 397) serves as the chief medium of transportation throughout the body. In the plasma, several different kinds of blood cells are suspended.

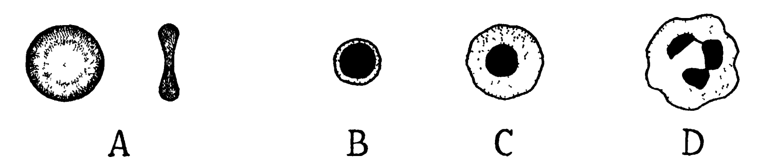


FIG. 171.—Red and white blood corpuscles of man, all drawn to the same scale. A, red blood corpuscle, flat and edgewise; B, lymphocyte; C, mononuclear leucocyte; D, polymorphonuclear leucocyte.

The *blood cells* of verterbrates are of three types. (1) The *erythrocytes*, or red corpuscles, contain large quantities of *haemoglobin*, the red pigment which facilitates the transportation of oxygen. (2) The *leucocytes*, or white corpuscles, are amoeboid cells, which in some cases can ingest bacteria and other foreign particles, thus counteracting infections, and preventing the blood vessels from clogging. (3) The *blood platelets*, or thrombocytes, are fragile colorless corpuscles, which initiate a clotting of the plasma—by disintegrating as soon as blood is shed (see p. 402).

Invertebrate bloods do not contain erythrocytes, although haemoglobin (or allied respiratory pigments) may be present —dissolved directly in the plasma. The erythrocytes of most vertebrates possesses nuclei.

Leucocytes are of various kinds according to their form and origin (p. 401); and not all leucocytes are able to migrate through the walls of the capillary blood vessels into the tissue spaces. The lymph—or body fluid, as it is more frequently called in lower animals—resembles blood, except that lymph contains

less protein, and no erythrocytes. Lymph fills the tissue spaces; and in a majority of animals, the lymph circulates slowly through these tissue spaces (p. 419).

TEST QUESTIONS

1. Distinguish carefully between:
   a. the vitelline membrane and the fertilization membrane;
   b. activation and fertilization;
   c. activation and parthenogenesis;
   d. natural and artificial parthenogenesis;
   e. haploid and diploid parthenogenesis.
2. Describe an experiment proving that activation and fertilization are separate functions of the sperm.
3. What is a blastula? How does the blastula derived from a homolecithal egg differ from one derived from a telolecithal egg (e.g., a frog's egg)?
4. What is a gastrula and how does it arise? Identify: (a) the archenteron, (b) the ectoderm and endoderm, and (c) the blastopore and blastocoel.
5. Explain three ways in which mesoderm may arise in various embryos.
6. Differentiate between diploblastic and triploblastic animals, citing an example of each.
7. Enumerate the adult structures (in vertebrate animals), which are derived from: (a) the ectoderm; (b) the endoderm; (c) the mesoderm.
8. A. Describe the origin of the coelom and explain how the coelom is related to the somatic and visceral layers of mesoderm, and to the mesentery.
   B. Explain the importance of the coelom in higher animals generally.
9. Explain the distinctive features which differentiate:
   a. vertebrates from invertebrate animals;
   b. vertebrates from other chordate animals.
10. Identify, locate, and explain the origin of:
    a. the neural groove, the neural folds, and the neural tube;
    b. the brain and spinal cord;
    c. the notochord;
    d. the vertebrae, including the neural arches and centra;

e. visceral and skeletal muscle;
f. the gill slits and the Eustachian tubes;
g. the lungs, liver, and pancreas;
h. the blood and lymph vessels.

11. Trace the development of the digestive tract (in vertebrates) from the time of invagination until the saccular enteron becomes tubular.
12. What are the *fundamental tissues* and how are they differentiated one from another?
13. Specify four kinds of epithelia and explain the distinctive features of each.
14. Specify the three kinds of muscle tissue and describe the distinctive features of each kind. In what ways are all kinds of muscle similar to each other?
15. Identify: (a) yellow fibrous connective tissue, (b) fibroblasts, (c) chondrin, (d) chondroblasts, (e) Haversian canals, and (f) lacunae.

FURTHER READINGS

1. *Ourselves Unborn,* by George W. Corner; New Haven, 1944.
2. *Embryos and Ancestors,* by G. R. DeBeer; Oxford, 1940.

CHAPTER 15

THE DIGESTIVE SYSTEM IN MAN AND OTHER MULTICELLULAR ANIMALS

THE SIMPLEST animals carry on ingestion, digestion and the other processes of their nutrition entirely within the limits of the single cell. But higher animals have developed specialized multicellular organs which display various degress of complexity and efficiency. Moreover, these organs are subordinated into definite organ systems; and well-defined *digestive*, *circulatory*, *respiratory* and *excretory systems* are recognizable in all higher animals. First to be considered will be the *digestive system*, which fulfills the functions of *ingestion*, *digestion*, *absorption* and *egestion*, in multicellular animals generally.

The Gastric Vacuoles of Primitive Metozoa. The earliest multicellular animals did not develop a new type of digestive cavity, but depended upon gastric vacuoles, essentially similar to those found among the Protozoa. This is particularly true of the *Porifera*, a primitive phylum of animals which commonly are called the *sponges*.

The cells of a sponge are aggregated in the form of a porous tube, which may or may not be complexly branched (Fig. 172). The tube is closed at the lower end, but communicates with the outside water through the *osculum*, a large opening at the upper extremity; and also there are many small *pores* in the side walls of the sponge. The entire tube is lined internally with flagellated cells (Fig. 173). These set up a stream of water which enters through the pores and leaves through the osculum (Fig. 172). The flagella also serve to waft small particles of food into the "collars" (Fig. 173), whence these particles pass

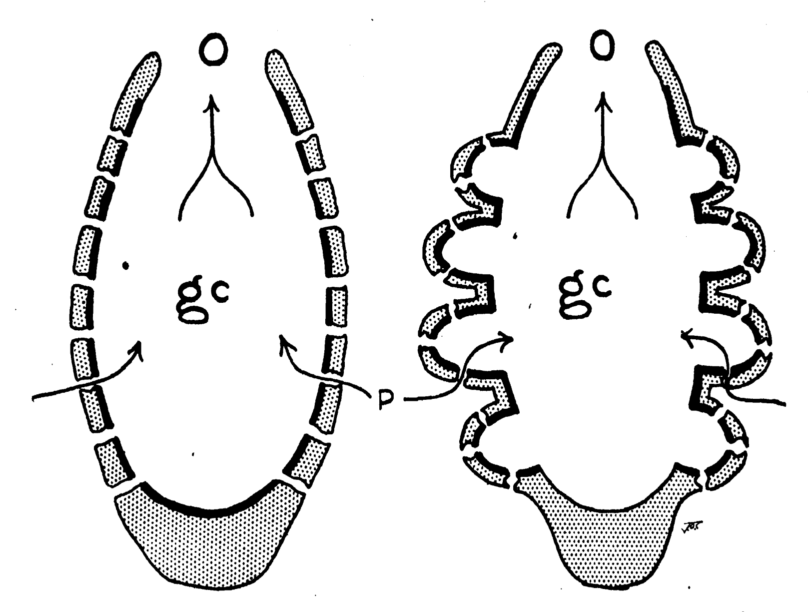
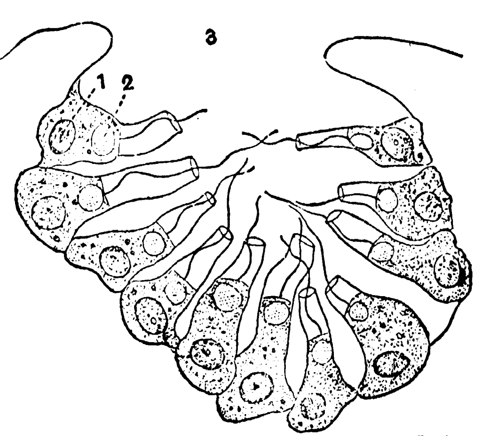


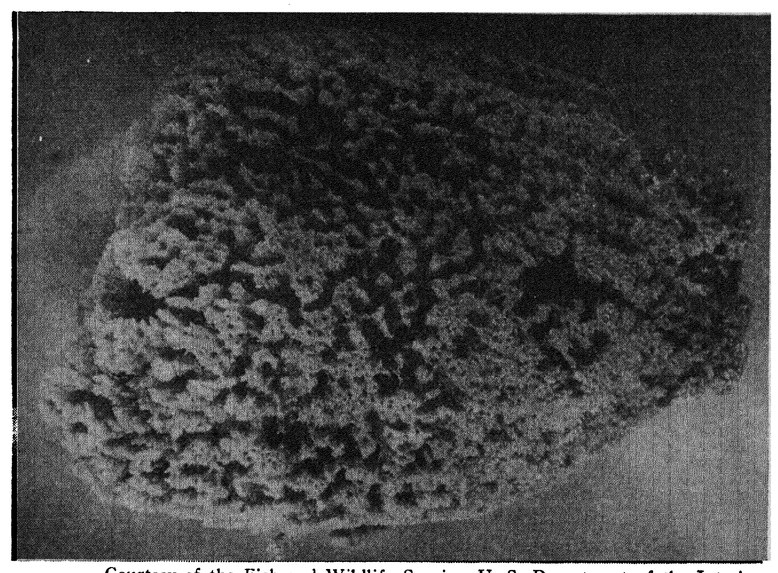
FIG. 172.—The canal systems of two relatively simple sponges. o, osculum; gc, gastrovascular cavity; p, pore. Arrows indicate the flow of water.



From Newman, *Outlines of General Zoology.*
By permission of The Macmillan Co.

FIG. 173.—Section of the flagellated chamber of a sponge, highly magnified to show collar cells and flagella. 1, nucleus of collar cell; 2, vacuole in collar cell; 3, flagellated chamber. (After Shipley and MacBride.)

into gastric vacuoles in the individual cells. Here the colloidal foods are digested. Part of the glucose, amino acids, and other products of digestion are utilized by the cells in which they are liberated, but part passes by osmosis to the neighboring cells. No parts of the body are very remote from the source of absorption. The wall of the body is composed of only two cell layers,



Courtesy of the Fish and Wildlife Service, U. S. Department of the Interior

FIG. 174.—Yellow sponge. The skeletal material of this sponge is *spongin*, a silklike compound. (The osculum lies to the left.)

although some sponges have a fair amount of relatively inert material, the *mesoglea*, interposed between the outer and inner cell layers. In commercially valuable sponges (Fig. 174), the mesoglea is composed of a silklike protein substance (*spongin*); but in others the skeletal material is calcareous, or silicaceous, according to the species.

The Saccular Digestive Systems of Hydra and Planaria. In simplest form, the saccular type of digestive cavity is found in the fresh-water polyp, *Hydra*. Essentially this small familiar aquarium animal has the form of a sac, in which only one opening, the *mouth*, communicates with the surrounding water

(Fig. 175). The *body wall* of Hydra is composed of only two cell layers; but between the outer *ectodermal epithelium* and inner *endodermal epithelium*, there is a thin layer of non-living matrix, the *mesoglea*.

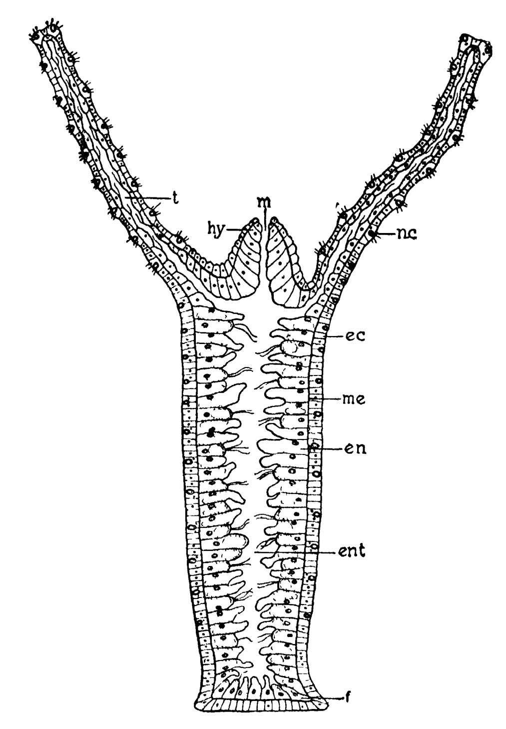


FIG. 175.—Hydra, longitudinal section. ec, ectodermal epithelium; en, endodermal epithelium; me, mesoglea; ent, enteron; m, mouth, hy, hypostome; t, tentacle; f, foot; nc, stinging cell.

Hydra captures a variety of small free-swimming animals by means of *tentacles*, a group of slender mobile threadlike organs which originate from the body in the region surrounding the mouth (Fig. 34). Each tentacle is armed by numerous evenly arranged batteries of *stinging cells* (Fig. 175). When the stinging cells discharge, they inject a paralyzing fluid into such victims as may happen to swim into contact with one of the waving tentacles. Then the tentacles push the immobile prey into the mouth, which can be opened very wide when necessary.

The *ingested* food of Hydra tends to accumulate in the saccular enteron, which is also called the *gastro-vascular cavity*. *Digestion* begins in the gastro-vascular cavity, but is completed in the separate cells lining the cavity, which form gastric vacuoles on an individual basis. Some of the epithelial cells are unicellular glands, which secrete enzymes into the gastro-vascular cavity. These enzymes appear to act primarily upon the connective tissues of the ingested organism, and gradually the body of the prey disintegrates into many small pieces. Then the epithelial cells, which are flagellated, begin to form food vacuoles, and the fragments of the food organism are ingested for a second time. In the individual food vacuoles, digestion is completed. The complex protein, carbohydrate and lipid components of the food are hydrolyzed, forming absorbable end-products, which diffuse to the neighboring cells of the Hydra. Non-digestible remnants of the food mass are passed from the vacuoles back into the gastro-vascular cavity and out into the environment via the mouth.

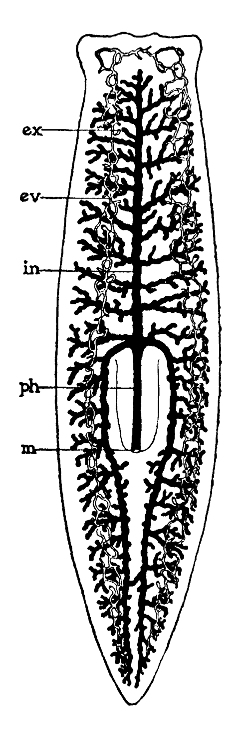
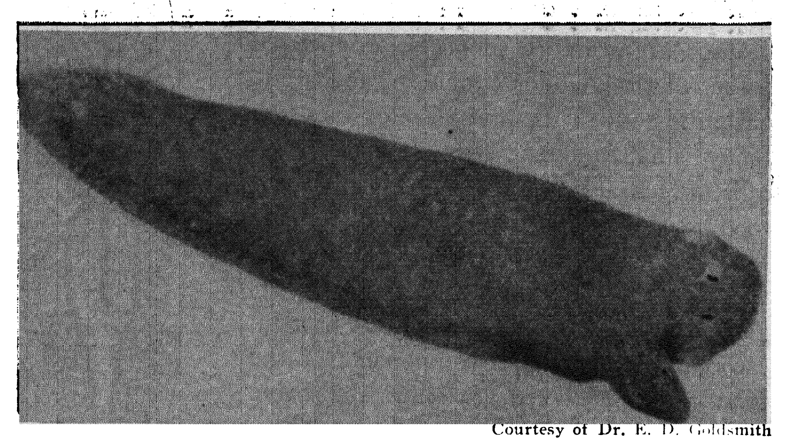


FIG. 176. — Planaria, digestive and excretory systems. m, mouth; ph, pharynx; in, gastro-vascular cavity; ev, excretory vessel; ex, excretory pore.

The saccular type of enteron, in which the mouth opening serves for both ingestion and egestion, has a fairly wide distribution among primitive kinds of animals. It is possessed not only by Hydra and other Coelenterates (p. 351), but also by the flatworms or Platyhelminthes (p. 741). Among flatworms, however, the gastro-vascular cavity is not a simple sac, but a branched system of blind pockets all connected by main channels which lead inward from the mouth (Fig. 176).

The branched type of gastro-vascular cavity is well exemplified by Planaria, one of the commonest of the free-living flat-

worms. This graceful little animal (Fig. 177) has a flexible ribbon-like form. The ciliated *epithelium*, which covers the body externally, enables the Planaria to glide through the water, with the flat ventral surface in contact with rocks and other objects on the bottom of the pond. The anterior end, or head, is broader than the tapered tail and the dorsal surface has a darker color than the ventral. A pair of light-sensitive *eye-spots* are located



Courtesy of Dr. E. D. Goldsmith

FIG. 177.—Specimen of Planaria, on which an extra head has been induced to form, due to a localized injury.

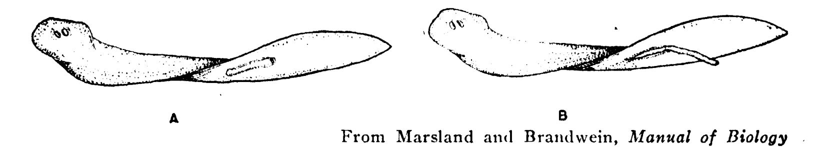
on the dorsal surface near the anterior end of the head; and on each side of the head there is a small blunt-pointed lateral projection, the *auricle*, which is thought to be a receptor of tactile stimuli.

The *mouth* of Planaria is found at the tip of a hose-like muscular organ, the *pharynx* (Fig. 178). The pharynx protrudes out from the ventral surface only when the Planaria is feeding; and at all other times it is withdrawn into the *pharyngeal pouch* (Fig. 178).

Planaria feeds upon minute organisms and particles of organic matter on the bottom of the pond. The food passes through the mouth and pharynx into the branches of the gastro-vascular cavity. The full extent of this branching system can be demonstrated by injecting an ink suspension through the mouth and

pharynx, by means of a hypodermic syringe. Then it can be seen that the many branches of the digestive cavity penetrate to all parts of the body (Fig. 176).

The branching of the gastro-vascular system facilitates the distribution of the absorbed foods to the outlying cells of the animal. The body of the flatworm, compared to Hydra, is considerably thicker, because a layer of *mesoderm* develops between the ectoderm and endoderm (Fig. 179). In Planaria, the mesoderm consists mainly of loosely arranged *parenchyma* tissue, which surrounds the various structures of the muscular, nervous, reproductive, and excretory systems. The intercellular spaces of the mesoderm are filled with a body fluid, which distributes food substances absorbed from the numerous branches of the gastro-vascular cavity. Distribution is accelerated by the movements of the body, which set up haphazard currents in the body fluid; but there is not any very definite or sustained circulation of the body fluid of the Planaria.



From Marsland and Brandwein, *Manual of Biology*

FIG. 178.—Planaria, A, with pharynx retracted; B, with pharynx extended.

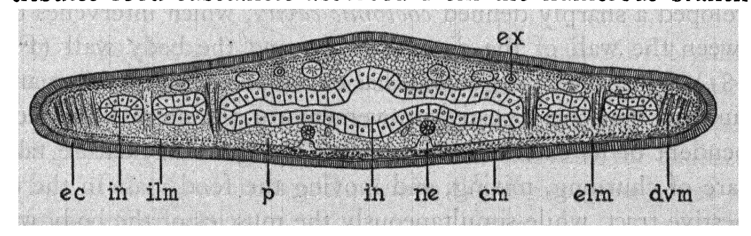


FIG. 179.—Planaria, cross-section. ec, *ectoderm;* en, *endoderm;* in, gastro-vascular cavity; p, parenchyma; cm, circular muscles; elm and ilm, external and internal longitudinal muscles; dvm, dorso-ventral muscles; ne, nerve cord; ex, excretory vessel. The other, unlabeled, organs embedded in the mesoderm are parts of the reproductive system.

The Tubular Digestive Tract of the Earthworm. All animals above the evolutionary level of the flatworms possess

a tubular type of enteron, generally similar to the digestive tract of man. Such tubular systems allow for a one-way passage of food materials from the mouth to the anal opening. Food ingested through the mouth undergoes digestion and absorption as it moves along the length of the enteron; and finally the remnants of the food are egested through the anus.

The earthworm and other Annelids (p. 742) possess a simple tubular enteron (Fig. 180) which illustrates the advantages of such a system. Annelids, like higher forms generally, have de-

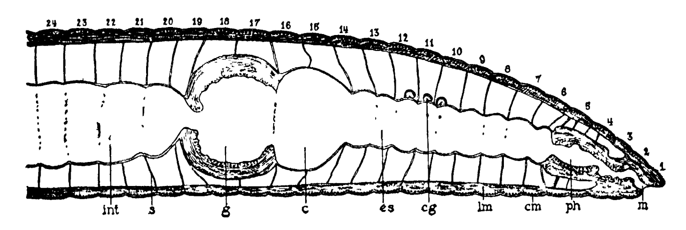


FIG. 180.—Earthworm, anterior portion of the digestive system in longitudinal section. m, mouth; ph, pharynx; es, esophagus; cg, calciferous gland; c, crop; g, gizzard; int, intestine; s, septum. The numbers indicate the segments; all the posterior segments are similar to the last ones shown.

veloped a sharply defined *coelomic cavity*, which intervenes between the wall of the digestive tract and the body wall (Fig. 181). Moreover, the gut wall has developed a separate musculature, so that the digestive movements of the animal are independent of its external movements. The gut musculature takes care of churning, mixing, and moving the food mass in the digestive tract, while simultaneously the muscles of the body wall are executing the various external responses of the animal.

Tubular enterons are variously modified in different higher animals. In the earthworm, the *pharynx* lies directly behind the mouth and displays a relatively thick muscular wall (Fig. 180). The pharynx acts as a sort of suction pump which expands and contracts, sucking in small masses of moist earth as the worm burrows into the soil. The ingested earth, which contains considerable rotting plant material, mixed with the hard soil particles, then passes through the straight cylindrical *esophagus* (segments 6-14) to a thin-walled distensible chamber, the *crop*.

While passing through the esophagus the food mass is mixed with the juices from three pairs of *multicellular glands*, the *calciferous glands* (Fig. 180). These secretions are rich in calcium carbonate, which probably neutralizes the acids present in many soils. When the crop accumulates sufficient food, it passes the mass on to the thick-walled *gizzard* (segments 17-18), which is a grinding organ. The grinding action of the gizzard results from the strong rhythmic contractions of its thick muscular walls. Bits of leaves and other small masses of organic material are cut to smaller and smaller pieces, because they are repeatedly compressed between the sharp particles of the soil. This grinding action is important because it increases the exposed surface of the food mass and permits the digestive enzymes to act more effectively.

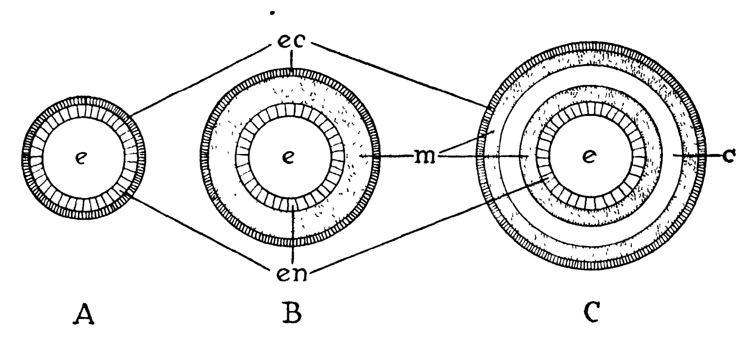


FIG. 181.—Diagrams of cross-sections of (A) Hydra, (B) Planaria, and (C) earthworm. ec, ectoderm; en, endoderm; m, mesoderm; e, enteron; c, coelom.

The *intestine* of the earthworm is the last and longest part of the digestive tract (Fig. 180). This thin-walled tube extends straight back from the gizzard to the anal opening, at the posterior extremity of the worm. While the food mass moves slowly along the intestine, digestion and absorption are completed. Many unicellular glands are present in the epithelial lining of the intestine, and these glands secrete carbohydrases, proteases, and lipases upon the passing food. The sugars, amino acids, glycerol and other relatively simple end-products, derived from the hydrolysis of the organic foods, dissolve in the water

fraction of the moist food mass; and as these end-products accumulate, they tend to be absorbed by osmosis, through the endoderm into the blood, which flows continuously through the capillaries in the wall of the intestine.

The Digestive Tract of Man. The human digestive tract, like that of Vertebrates generally, is a tubular system, possessing a characteristic number and arrangement of the several parts (Fig. 182). Food is ingested through the mouth into the *oral cavity*, where it is chewed and mixed with saliva (Fig. 182). Then the food is swallowed and passes quickly through the short *pharynx* and the long *esophagus* to the *stomach*. The stomach is a thick-walled muscular saclike portion of the enteron, which churns the food mass sometimes for as long as 5-6 hours, while the food is acted upon by the *gastric juice*. This juice pours into the stomach cavity from thousands of microscopic glands, the *gastric glands*, which line the stomach wall (p. 370). When the food has been reduced to fluid form, it is passed on into the *small intestine* (Fig. 182). This long (23 ft.) and relatively narrow part of the digestive tract is highly coiled; and the many coils of the small intestine are all crowded together in the abdominal cavity. The small intestine receives the food mixture from the stomach and, in the course of about 10 hours, transmits the remnants of the food to the *large intestine* (Fig. 182). Meanwhile, *pancreatic juice* from the *pancreas* and *bile* from the *liver* (Fig. 182) are poured upon the food while it passes through the very first part of the small intestine; and the *intestinal juice*, from the numerous microscopic *intestinal glands* in the intestinal wall, is added further along in the tract. When the food mixture reaches the large intestine, digestion has been completed and most of the end-products of *digestion* have been *absorbed*. But while the remnants of the food pass through the large intestine to the *rectum* (Fig. 182), much of the residual water is absorbed. Accordingly, when the mass is *egested* through the *anus*, it usually displays a semi-solid consistency.

Microscopic Structure of the Digestive Tract. Although the various parts of the digestive tract are superficially quite different, all parts display a similar histological structure. In

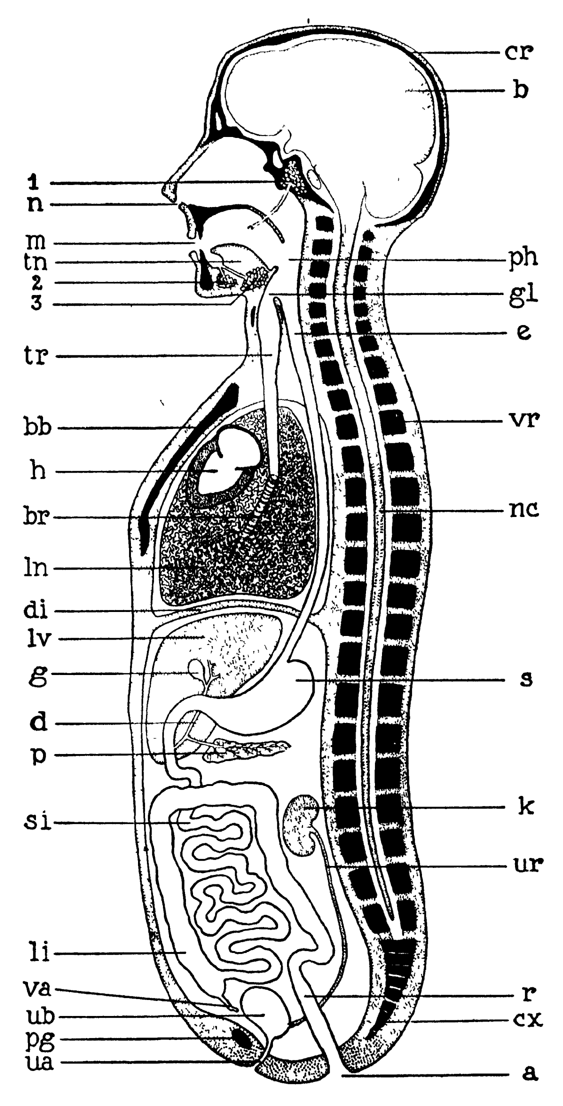
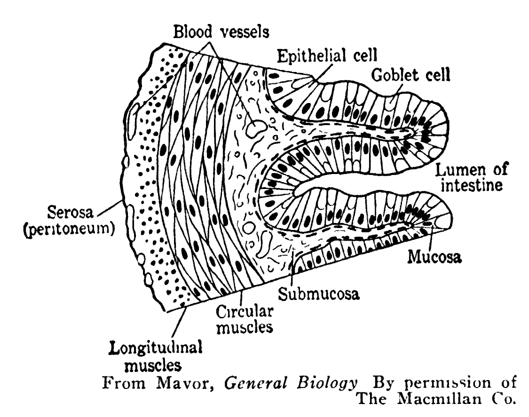


Fig. 182.—Diagrammatic longitudinal section of man. n, nostril; m, mouth; tn, tongue; 1, 2, 3, salivary glands (1—parotid; 2—sublingual; 3—submaxillary); ph, pharynx; gl, glottis; tr, trachea; br, bronchus; ln, lung; di, diaphragm; h, heart; e, esophagus; s, stomach; lv, liver; g, gall bladder; d, bile duct; p, pancreas; si, small intestine; li, large intestine; va, vermiform appendix; r, rectum; a, anus; k, kidney; ur, ureter; ub, urinary bladder; ua, urethra; nc, nerve cord (spinal cord); b, brain; cr, cranium; vr, vertebra; cx, coccyx (vestigial tail vertebrae); bb, breastbone; pg, pelvic girdle.

fact the enteron wall is formed throughout by four concentric layers, which are named from within outwards: (1) the *mucosa,* (2) the *submucosa,* (3) the *muscularis,* and (4) the *serosa.* In the frog's intestine, for example, one finds the same four layers as in the human digestive tract, although the intestinal wall of the frog (Fig. 183) is relatively simple, compared to that of man. The *mucosa,* or innermost layer of the enteron wall, comes into direct contact with the food in the digestive tract; although



From Mavor, *General Biology* By permission of The Macmillan Co.

FIG. 183.—Part of a cross-section of a frog's intestine. (After Holmes.)

the mucosa of the frog is represented by a single layer of glandular epithelium, which is derived entirely from the endoderm (Fig. 183).

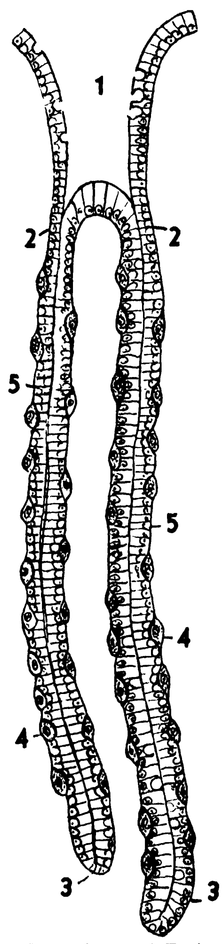
The other three layers of the enteron wall are all derived embryologically from mesoderm. The *submucosa* consists mainly of fibrous connective tissues, although it is abundantly supplied with blood capillaries and lymph vessels, which absorb food substances through the mucosa. The *muscularis* (Fig. 183) consists of two sheets of visceral muscle, which effect the movements of the bowel. The inner part of the muscularis is called the *transverse* layer, because its fibers tend to encircle the enteron; but the fibers of the outer part run lengthwise of the intestine, and these make up the *longitudinal layer* of the muscularis. The *serosa* is a single tier of flattened epithelial cells, which provides a smooth external lining for the enteron. A

serous fluid is secreted by the serosa, and this fluid lubricates the abdominal surfaces, reducing the frictional irritation as the coils of the intestine rub against each other and against the other organs of the abdominal cavity.

Glands of the Digestive Tract. Many of the cells of the mucosa are *goblet cells* (Fig. 165), or *unicellular mucous glands.* Each goblet cell produces a small globule of mucus periodically, and extrudes this secretion upon the food mass. Collectively the mucosa produces considerable quantities of mucus, which serves as a lubricant, facilitating the passage of food through the digestive tract.

The other digestive glands represent multicellular outfoldings of the endodermal epithelium. The *gastric glands* (Fig. 184) and the *intestinal glands* are *simple* glands, in that they are microscopic and lie entirely in the wall of the digestive tract; but the salivary glands, liver, and pancreas are *compound* glands; and these large separate organs are connected to the digestive tract only by their *ducts* (Fig. 182, 3).

The Oral Cavity. The main structures of man's oral cavity are quite familiar. The *palate,* or "roof of the mouth," is a partition which separates the oral cavity from the *nasal passages* (Fig. 182). The anterior bony part of this partition is the *hard palate;* but the posterior non-bony part is the *soft palate,* which terminates as a fleshy projection, the *uvula.* The oral cavity is guarded in front by the *lips,* and flanked at the sides and in front



From Best and Taylor, *The Living Body*

FIG. 184.—Glands from fundus of stomach. 1, pit on mucous surface of stomach; 2, neck of gland; 3, bottom (fundus) of gland; 4, cells which produce HCl; 5, enzyme-producing cells.

by the upper and lower sets of *teeth*. The *tongue*, which is a flexible muscular organ, arises from the floor of the mouth; and the *mucosa* lines the oral cavity throughout, except in the region of the gums and lips—where the lining represents a sort of modified skin. The oral mucosa is continuously moistened by the mucous secretions of its own goblet cells and by *saliva*, which drains into the mouth from the *salivary glands* (Fig. 182).

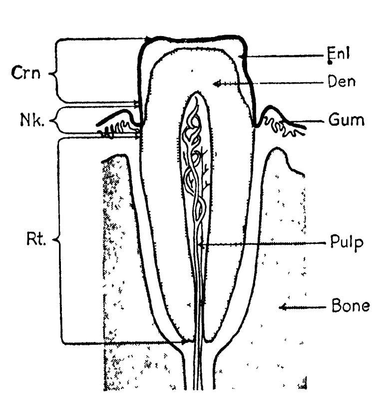


FIG. 185.—Structure of a human tooth. Enl, enamel; Den, dentine; Crn, crown; Nk, neck; Rt, root.

The Teeth. The teeth of different vertebrates are adapted to the food habits of the individual; but all vertebrate teeth conform to a common structural pattern. The part of a tooth that projects above the gum level is called the *crown* (Fig. 185), which is made up of three layers: (1) the *enamel*, an external covering of exceedingly dense hard material; (2) the *dentine*, an intermediate layer of bonelike matter, not quite so hard as the enamel; and (3) the *pulp*, a soft tissue (including the nerves and blood vessels of the tooth) which fills the central *pulp cavity*. The part of a tooth which is encircled by the fleshy *gum* tissues is called the *neck;* and below the neck lies the *root*, which fits snugly into a *socket*, provided by the jaw-bone. In composition the root resembles the crown, except that the enamel is replaced by *cement*, a material that binds the dentine to the bone of the jaw.

Vertebrate teeth arose among primitive fish, from scale-like structures, called *placoid scales*. Such scales are found in the modern sharks and other cartilaginous fishes, but not in the bony fishes. The sharks have many rows of teeth, which rim the mouth in the region where the skin folds inward into the oral cavity; and these teeth are replicas of the smaller placoid scales which cover the entire body surface. The shark's teeth dis-

play the same structural layers as other vertebrate teeth; but in higher vertebrates, the teeth have become variously modified in form, to fit the food habits of the particular species.

The *permanent* teeth of adult *man* are normally 32 in number; i.e., there are 8 teeth on each side of both the upper and the lower jaws (Fig. 186). Each group of eight consists of: (1) two *incisors*, the chisellike *cutting teeth*, in the front of the jaw; (2) one *canine*, the blunt-pointed tearing tooth, at the side of the incisors; (3) two *pre-molars*, the *simple* grinding teeth, behind the canines; and (4) three *molars*, the *complex* grinding teeth, behind the pre-molars (Fig. 186). However, the third molars, or wisdom teeth, sometimes fail to erupt beyond the gum level. In man and other Mammals (p. 744), the permanent teeth are preceded by the *milk teeth*, which resemble the adult teeth, except that the molars are not represented.

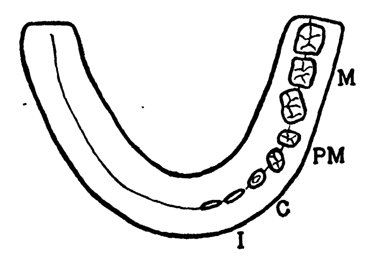
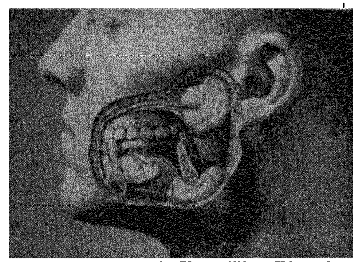


FIG. 186.—Diagram of the dentition of man. I, incisors; C, canine; PM, premolars; M, molars. The same kinds of teeth are duplicated on the other side of the lower jaw and on the two sides of the upper jaw.

The dentition of man is generally similar to that of the other Mammals; but in different Mammals the dentition is variously modified according to the food habits of the species. In Rodents (squirrels, mice, etc.), for example, the incisors, or gnawing teeth, are very prominent. Herbivorous animals (horses, cows, etc.) also have well-developed incisors with which to *crop* the vegetation—and even more particularly—herbivorous animals have very conspicuous molar teeth, to *grind* and *pulp* the vegetation in preparation for swallowing. Carnivorous animals (such as wolves and tigers) have very prominent canine teeth, which serve for *tearing* flesh from the victim, as well as for offensive and defensive purposes. Man, however, is quite omniverous in his food habits; and the dentition of man is very conservatively balanced.

As it is chewed, the food is cut and ground thoroughly, which increases the surface exposed to the action of the saliva and other digestive juices. Chewing also mixes the food with the saliva and converts the whole food mass into a pulp which can be swallowed without difficulty.

The Tongue. The tongue, essentially, is a mucosa-covered mass of intricately arranged muscle fibers, which can be shaped and moved in a very agile manner. The role of the tongue in shaping our speech—especially when we ask for food—is related indirectly to nutrition; but the tongue also has three direct nutritional functions: (1) the tongue manipulates the food during chewing, so that each morsel is kept in range of the proper teeth; (2) the tongue shapes the chewed food into a pulpy mass, the *bolus*, and squeezes the bolus into the pharynx, when it is time for swallowing; and (3) the mucosa of the tongue provides a housing for a majority of the *taste-buds* (p. 542).



...nd film, *The Digestion of Foods*, the Encyclopaedia Britannica Films, Inc.

FIG. 187.—Drawing of the salivary glands superimposed upon a photograph. The sublingual gland, lower front; the submaxillary gland, lower back; the parotid gland, above.

The Salivary Glands. Man and most other Mammals possess three pairs of *salivary glands*, which secrete the *saliva* and send it into the oral cavity. The salivary glands of man include: (1) the *parotid* glands, which lie embedded in the soft tissues of the cheeks, just below and behind the "cheek-bones"; (2) the *submaxillary* glands, which are embedded in the floor of the mouth, in front of the angles of the lower jaws; and (3) the *sublingual* glands, which also lie in the floor of the mouth, along the sides of the tongue (Fig. 187). Each gland is a lobulated mass of glandular tissue, weighing about one ounce; but the salivary glands jointly produce about two quarts of saliva daily. The saliva drains from the glands via ducts. A single duct from each parotid opens upon the inner surface of the cheek

opposite the second upper molar; whereas the duct from each submaxillary, and the several ducts from each sublingual, drain upon the floor of the mouth, near the roots of the lower canine teeth (Fig. 187).

Composition and Functions of the Saliva. The composition of human saliva, based on an anlysis of the mixed juices of all the glands, is given in Table XI. This shows that saliva,

TABLE XI

HUMAN SALIVA; AVERAGE COMPOSITION

Components	*Per Cent by Weight*
Water	99.5
Inorganic salts (mainly chlorides, bicarbonates and phosphates of sodium, potassium, and calcium)	0.2
Inorganic gases: oxygen and carbon dioxide	Traces
Organic substances	
Enzymes: *ptyalin* and *maltase*	Traces
Other proteins: mucin, globulin, albumen	0.2
Wastes: urea, etc.	Traces

Reaction: slightly acid (*pH* 6.5-6.8)

like all other digestive juices, contains a large proportion of water—which serves as a solvent for all other components of the juice.

The functions of saliva are partly chemical and partly mechanical. Among the chemical reagents in saliva, the enzyme *ptyalin* is a very active amylase. Thus if a suspension of boiled starch is incubated at body temperature with a few drops of saliva, a hydrolysis of the starch to *maltose* is completed within about 20 minutes. The opaque starch suspension gradually becomes first translucent and then transparent, which indicates that the large starch molecules are decomposing into smaller and smaller fragments. Finally all the starch is converted into maltose. Moreover, some of the maltose is converted to glucose, since human saliva contains small amounts of the enzyme, *maltase.*

As to its mechanical functions, saliva facilitates swallowing by *softening* and *lubricating* the food; and by *binding* the separate

food particles into a plastic mass, the *bolus*, which can be swallowed as a whole. Thus when the flow of saliva is inhibited—as by fright—a cracker or other *dry* food can scarcely be swallowed. Also saliva augments *taste*. The taste-buds are sensitive only to dissolved substances; and by dissolving the dry components of the food, the saliva brings out their taste.

A small flow of saliva continues even between meals. This flow is important because it *cleanses* the mouth, preventing an encrustation of the teeth and tongue with food particles, bacteria, scuffed-off epithelial cells, and other detritus of the oral cavity. Thus if salivation is inhibited for a long period, as occurs in certain fevers, the mouth tends to foul, unless it is washed at frequent intervals. The continuous flow of saliva also lubricates the tongue during speech—for if the saliva does not flow properly the tongue is apt to "cling to the roof of the mouth."

The Salivation Reflex. The main flow of saliva occurs at mealtimes; and the activity of the salivary glands is controlled entirely by the nervous system. Other digestive glands (see p. 377) are also activated by *hormones*, which exert a slower and more sustained effect. But the flow of saliva must occur very rapidly, while the food is in the mouth; and consequently salivation is entirely a *reflex* act, which is effected through the nervous system.

The main receptor-conductor-effector pathway of a *salivation reflex* is shown in Fig. 188. All flow of saliva is abolished, if the motor nerves to the glands are severed; or if the brain is damaged in the region of the salivation centers; and this experiment proves that the entire output of the glands is controlled by the nervous system—i.e., *no hormone is involved.*

The salivation reflex was used by the well-known Russian physiologist, Pavlov, in his early studies on reflexes generally. Pavlov worked on dogs in which the ducts of the salivary glands were brought to the outer surface of the cheeks—which permitted him to observe the flow of saliva whenever a suitable stimulus was applied. These studies led Pavlov to draw a distinction between the two main kinds of reflexes, which are called: (1) *conditioned reflexes* and (2) *unconditioned reflexes.*

If food, or anything associated with food, is shown to a very young puppy, or child, no salivation occurs; but the saliva promptly flows if anything—even a tasteless object—is placed directly in the mouth. This shows that the *primary receptors* of the salivation reflex are localized *in the mouth.* These primary receptors are mainly the *taste-buds* (p. 543), although the tactile

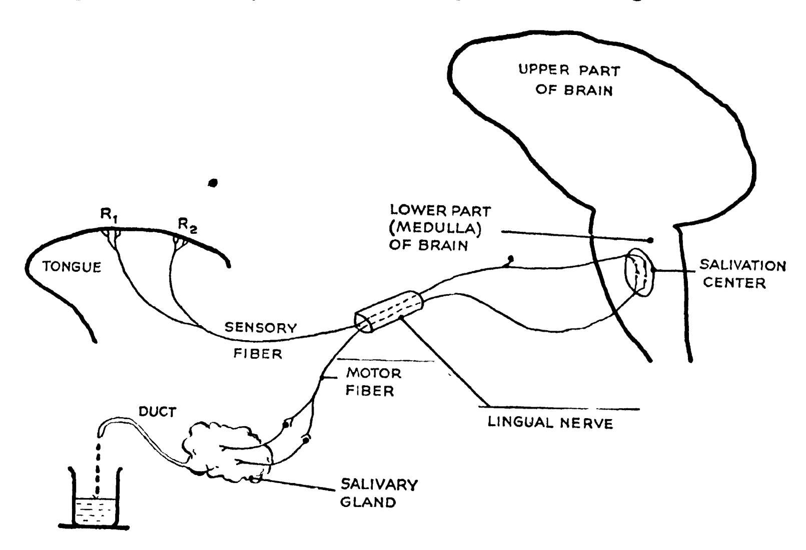


FIG. 188.—Diagram showing one of the pathways of the salivation reflex. Such a typical reflex involves a series of nerve cells, which convey impulses from the receptors, via the central nervous system, to the effectors. R1, R2, receptors, e.g., taste-buds.

receptors of the oral mucosa play a minor role. This type of reflex, which is obtainable in the absence of any previous training or conditioning, is called an *unconditioned* reflex. But Pavlov showed that in trained, or conditioned, animals, other types of stimulation—or more precisely other receptors—can be substituted for the primary receptors. Thus in older dogs or children, the sight or smell of food—or sounds associated with food—will cause the "mouth to water." These *conditioned reflexes* result from a frequent association between stimuli affecting the primary receptors and stimuli acting upon other (*secondary*) receptors of the body. After a period of conditioning, salivation is obtained merely by sounding a bell which previously is rung

each time a puppy is fed, or by showing any object that has been displayed at each feeding during the conditioning period. Thus in man and other animals, the salivation of an older individual represents a dual reflex. It is partly an unconditioned reflex, elicited by the food which is actually in the mouth; and partly a conditioned reflex, resulting from the sounds, sights, and smells which are regularly associated with eating.

The Pharynx and Esophagus. Most of man's digestive organs lie in the abdominal cavity, i.e., below the diaphragm; and the pharynx and esophagus carry the food quickly through the neck and thorax to the stomach (Fig. 182).

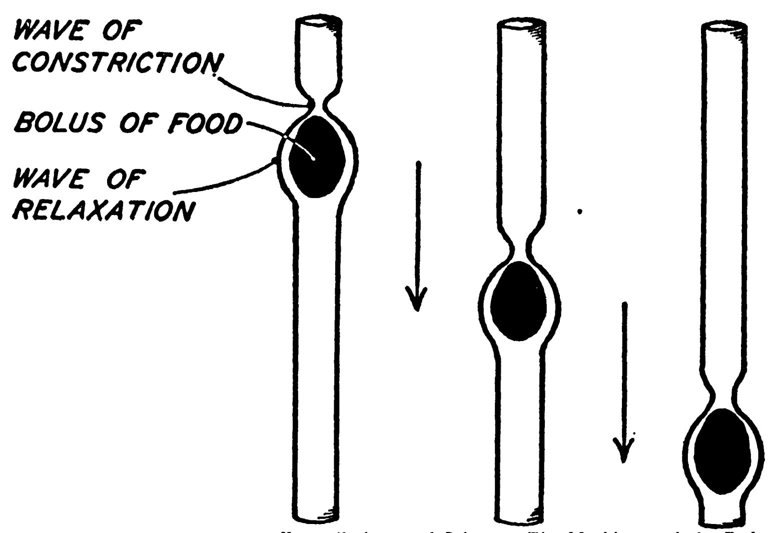
The *pharynx* is a very complex portion of the digestive tract, which conducts not only food from the mouth to the esophagus, but also air from the nasal passages to the *trachea* (Fig. 182). The pharynx originates immediately behind the palate, where the nasal passages join the digestive tract, and terminates in the upper part of the neck, where the trachea forks off from the food passage (Fig. 182). Moreover, the pharynx communicates with the *middle ear* chamber via the paired *Eustachian tubes.* The upper part of the trachea, where the wall is reinforced by a conspicuous housing of cartilage, is called the *larynx,* or "Adam's apple"—in which lie the vocal cords. The opening which conducts air from the pharynx to the larynx is a narrow channel, the *glottis,* above which lies a valvelike flap, the *epiglottis* (Fig. 182).

The *esophagus,* or gullet, is a thick-walled muscular tube that leads straight downwards through the neck and thorax, from the pharynx to the stomach. The muscular layers of the esophagus are well developed—being composed of *skeletal* muscle, in the upper ⅓ of the tube; and of *visceral* muscle, in the lower ⅔ of the length.

Swallowing is a complex series of unconditioned reflexes which sweep the bolus of food rapidly from the mouth to the stomach. The tongue initiates swallowing by molding the food mass into a bolus and projecting the bolus from the mouth into the pharynx. This part of the reflex is under voluntary control;

but the succeeding events, once started, cannot be stopped at will.

When a bolus comes in contact with the wall of the pharynx, it initiates a series of reflex movements which (1) closes off the air passages and (2) propels the bolus into the esophagus. The soft palate is elevated, closing off the nasal passages; and the



From Carlson and Johnson, *The Machinery of the Body*, by permission of the University of Chicago Press

FIG. 189.—Peristalsis in the esophagus. Three stages in the downward movement of a semi-solid bolus of food are shown.

larynx is raised, bringing the glottis under cover of the epiglottis and posterior part of the tongue. Then, while the tongue is pressed firmly against the roof of the mouth, the whole pharyngeal wall constricts, forcing the bolus into the esophagus.

In the esophagus the bolus is seized by a wave of muscular movement, which sweeps downwards toward the stomach. This wavelike type of movement is called a *peristaltic wave*, which is a characteristic movement in most parts of the digestive tract. Each typical peristaltic wave represents a slowly moving wave of *constriction*, involving only a short length of the wall of the digestive tract; but a similar wave of *dilatation* runs along the

tract, immediately in front of the wave of constriction (Fig. 189). The constriction represents a contraction of the circular layer of the mucularis, which squeezes the bolus before it; and the dilatation, which chiefly involves the longitudinal muscle, paces along ahead of the bolus, opening the tube at each moment to receive the moving food. In the esophagus the waves are unusually rapid, so that the food takes only about 6 seconds in passing through the esophagus to the stomach. In fact, liquids are swallowed even more quickly, because the esophagus tends to remain dilated while drinks are being swallowed, allowing the liquids to flow mainly under the force of gravity.

The Stomach. The *stomach* is a thick-walled muscular sac, which plays a very important role in digestion. The *muscularis* of the stomach contains a layer of *diagonal* fibers, in addition to the circular and longitudinal layers; and the gastric *mucosa* is pitted with an exceedingly great number of simple glandular outpocketings, the *gastric glands.* While the food remains in the stomach, it is churned and mixed with the *gastric juice;* and the stomach does not pass its contents on to the small intestine until the meal has been thoroughly liquefied as a result of many changes. The emptying of the stomach is relatively rapid (about 10 minutes) in the case of a drink of plain water; but some meals may take 3-4 hours in passing through the stomach, depending on the quality and quantity of the food.

The Size and Shape of the Stomach. The capacity of the stomach varies according to its contents; and during the ingestion of a meal the muscular walls expand to a maximum capacity of about 2½ quarts, in an average individual. Then during the digestion of the meal, the stomach gradually shrinks, as the semi-digested food is passed, little by little, into the small intestine. Finally the gastric cavity is practically obliterated; whereupon further peristaltic waves, in which the stomach merely squeezes down upon itself, give rise to "hunger pangs," and it is time to eat again.

The anatomy of the stomach is best described in terms of the half-filled organ, such as is outlined in Fig. 190. Such a stomach is distinctly J-shaped, and permits one to identify the *three*

main parts of the stomach. (1) The *fundus* is a small bulbous gas-filled chamber, which occupies the vertical limb of the J, above the opening from the esophagus; (2) the *cardiac* region consists of the remainder of the vertical limb; and (3) the

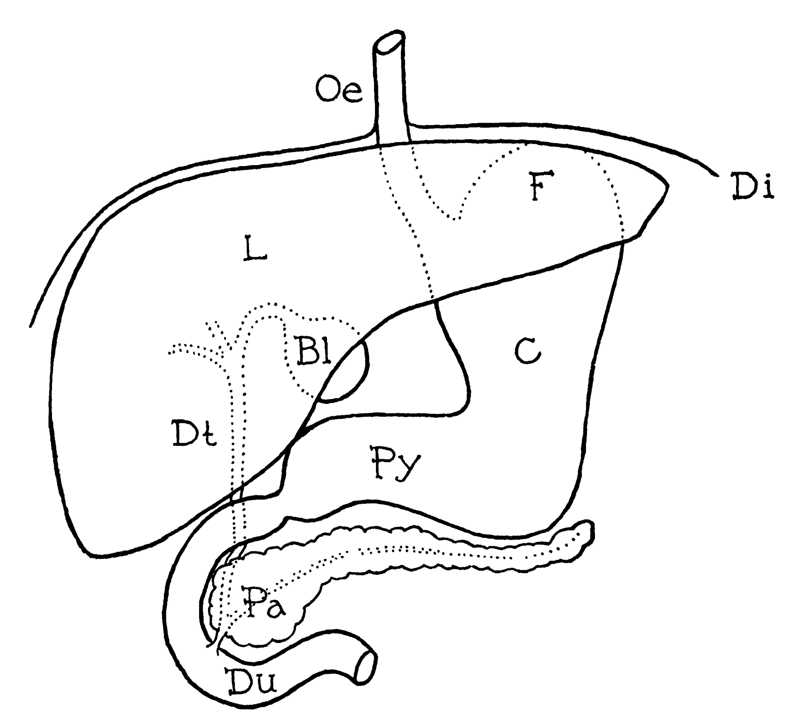


FIG. 190.—The stomach and duodenum in relation to the liver and pancreas in man. Oe, esophagus; F, fundic part of stomach; C, cardiac part of stomach; Py, pyloric part of stomach; Du, duodenum; L, liver; Bl, gall bladder; Dt, bile duct; Pa, pancreas; Di, diaphragm.

pyloric region extends from the "bend of the J" to the point where the stomach joins the *duodenum*, or first part of the small intestine. Guarding the entrance and exit channels of the stomach, there are ringlike bands of muscle: (1) the *cardiac valve*, which encircles the esophageal opening and prevents a regurgitation of food into the esophagus; and (2) the *pyloric valve*, which prevents food from passing out of the stomach into the duodenum, until the proper time. Both of these valves are typi-

cal *sphincter valves,* such as are found in other regions of the digestive tract, i.e., at the point where the small intestine leads into the large intestine, and at the anus. Essentially a sphincter represents a local thickening of the circular layer of the muscularis, which contracts and closes the passage, except at certain times, when the valve relaxes and allows the food mass to pass.

Nerve Supply of the Stomach. Like all the other *viscera,* or internal organs of the body, the stomach is supplied by two sets of nerves, both belonging to the *autonomic nervous system* (Chap. 24). These two sets of autonomic nerves have an antagonistic effect upon the gastric musculature and upon the secretion of the gastric glands. The *parasympathetic fibers* (p. 602) are carried to the stomach by the *vagus nerves,* which originate from the brain stem and pass along the sides of the esophagus to the stomach and small intestine. Impulses from these parasympathetic fibers augment—i.e., strengthen and accelerate—the gastric movements and increase the secretion of the gastric glands. But also, the stomach receives a number of delicate *sympathetic* nerves from the spinal cord (p. 603); and these sympathetic fibers depress the mobility of the gastric musculature and reduce the flow of gastric juice.

The Gastric Juice. The gastric juice is a powerful digestive fluid secreted by the gastric glands, of which there are about 35,000,000 in the human stomach. Each gastric gland is a minute tubular infolding of the mucosa, although several glands may be associated with each of the small pits which can be observed with a hand-lens, when the inner lining of the stomach is inspected (Fig. 184).

Two early studies on human gastric juice deserve to be mentioned specifically. In 1776 Spallanzani demonstrated the *chemical* potency of the juice; and this was important because previously the action of the stomach upon the food was thought to be entirely mechanical. Spallanzani swallowed porous wooden capsules filled with meat and other protein foods; and when the capsules were reclaimed and examined, it was found that the proteins gradually had dissolved and escaped from the capsule—

despite the fact that the food was entirely protected from mechanical influences by the rigidity of the capsule walls. Then in 1819 William Beaumont, an American Army surgeon, began a long series of studies on a patient with an unusual gastric fistula. A fistula is an artificial channel communicating between a part of the digestive tract and the exterior of the body. In the present case, the patient was a Canadian trapper named Alexis St. Martin, who had exploded a shot-gun into the pit of his stomach. The charge penetrated not only the body wall, but also the stomach wall; and when the wound healed the stomach and body walls adhered together, leaving a permanent fistula which led directly into the gastric cavity. A flaplike overgrowth of the body wall covered the external opening, so that food could be retained in the stomach and normal gastric digestion could proceed. At any given time, however, the valvelike flap could be lifted, permitting Beaumont to obtain a sample of the semi-digested food mass or to collect pure gastric juice—uncontaminated with any food.

Composition of Gastric Juice. The collection of gastric juice by means of a stomach-tube is now a routine procedure, carried out by the physician in the clinic or by the medical student in the physiology laboratory. An outstanding characteristic of the gastric juice is its extreme acidity (pH = 1.2-0.3); and a complete analysis of the juice shows the following average composition:

TABLE XII

COMPOSITION OF GASTRIC JUICE

Components	*Per Cent by Weight*
Inorganic	
Water	98.02
Hydrochloric acid (HCl)	0.50
Salts	1.03
Organic	
Mucin Enzymes (pepsin, rennin, lipase) Other proteins	0.45
	100.00

Functions of the Gastric Juice. The *digestive* functions of the gastric juice are all related to its enzymes, of which *pepsin* is the most important. This very potent *protease* is especially active in the initial stages of the hydrolysis of proteins. Pepsin splits each large protein molecule into a number of simple molecules, called *proteoses* and *peptones;* and this reaction, as catalyzed by pepsin, may be written:

$$1 \text{ mol. protein} + x \text{ mols. water} \xrightarrow[\text{HCl}]{\text{pepsin}} x \text{ mols.} \begin{cases} \text{proteoses} \\ \text{and} \\ \text{peptones} \end{cases}$$

The net result of the action of pepsin in the stomach is the conversion of the various complex and frequently insoluble protein components of the ingested food, into much simpler soluble compounds, the proteoses and peptones. Thus when a mass of coagulated egg albumen is incubated at body temperature in a test tube containing gastric juice, the egg albumen dissolves within about half an hour; and suitable tests prove that the large molecules of the albumen have decomposed into a much larger number of proteose and peptone molecules.

The presence of hydrochloric acid (or other acid) is essential to the activity of pepsin; and neutralized gastric juice displays very little peptic activity. The enzyme pepsin, as secreted by the cells of the gastric glands, is in an inactive form, called *pepsinogen;* but pepsinogen is converted into pepsin, when it comes into contact with an acid medium. The HCl also augments the activity of the other enzymes of the gastric juice; and perhaps the germicidal properties of this acid are important in counteracting infective bacteria ingested with the food.

In *Mammals,* the gastric juice contains an enzyme, *rennin,* which acts solely upon caseinogen, the main protein present in milk. When milk, which is the main diet of all *young* Mammals, comes into contact with the gastric juice, the milk is *curded* immediately. Essentially curding represents a chemical reaction whereby the soluble protein, *caseinogen,* is converted to an insoluble protein, *casein,* which comes out of solution as a fine flocculent precipitate. This action is important, because

curding delays the passage of the milk through the stomach, allowing time for pepsin to digest the casein to the same extent as other proteins. Were the milk to remain in its native fluid state, it would be evacuated too quickly from the stomach, since fluids such as water are passed on to the small intestine within a few minutes after they are drunk. Since ancient times, rennin extracts from calves' stomachs have been used in making certain cheeses; and the active component of modern "junket" preparations is rennin.

The presence of lipase in the gastric juice is debatable; and at best the *gastric lipase* has a very weak fat-splitting action, effective mainly upon finely emulsified fats, such as milk and cream. In adults, if adequate precautions are taken against a contamination of the gastric juice by juices regurgitated into the stomach from the small intestine, little, if any, lipase activity can be detected in the gastric juice.

Control of the Flow of Gastric Juice. The total quantity of gastric juice produced during the digestion of an average meal ranges usually between 400 and 800 cc. This copious flow is induced partly by a series of well-defined *reflexes* and partly by a *hormone*, which is called *gastrin*. The flow of gastric juice commences at the very beginning of a meal, and this early secretion of juice is mainly of a reflex nature. But the gastric juice continues to flow until the stomach is emptied; and this late sustained secretion is effected mainly by the gastric hormone.

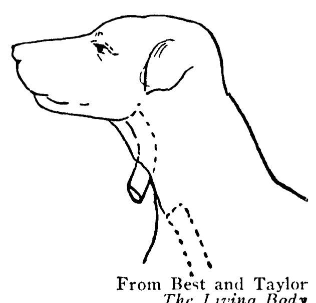
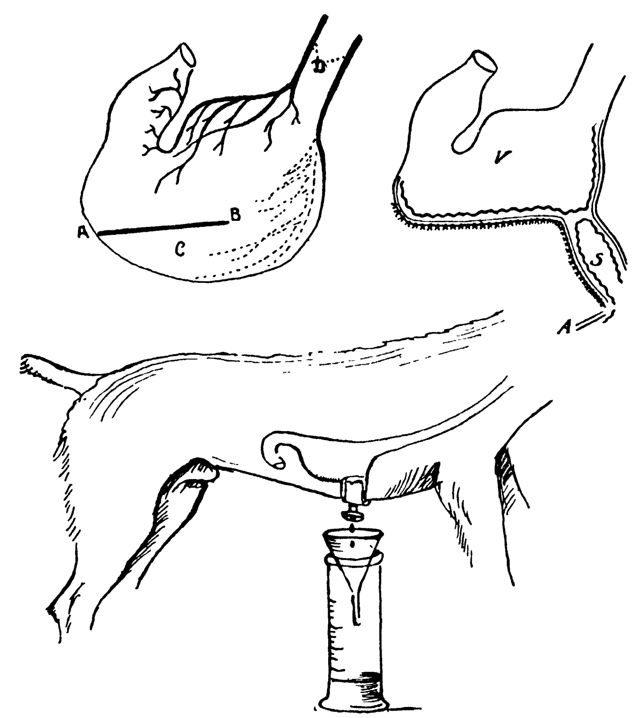

From Best and Taylor *The Living Body*

FIG. 191.—Showing an esophageal fistula, used in "sham feeding" experiments.

Pavlov was one of the first investigators to study the secretion of the gastric juice, and Pavlov devised the experimental techniques which are shown in Figs. 191 and 192. If a dog with an esophageal fistula (Fig. 191) is fed, the food of such a "sham-feeding" never reaches the stomach. Nevertheless about one-quarter of the normal flow of gastric juice takes place. This

fraction of the total gastric juice is entirely reflex in origin, since it is abolished when the gastric nerves are cut. Like salivation, this gastric reflex is partly unconditioned, involving the taste-



From Best and Taylor, *The Living Body*

FIG. 192.—Upper drawings show Pavlov's method of fashioning a gastric pouch, or miniature stomach. A horizontal incision (A-B) is made which causes minimal injury to the gastric nerves and blood supply. (D) vagus nerves. The flap (C) is turned down and the pouch (S) isolated by sutures from the main cavity of the stomach (V) as shown in the right-hand sketch. (A) abdominal wall. The lower drawing illustrates the manner in which pure gastric juice can be collected from the miniature stomach while digestion is proceeding in the main part of the stomach.

buds as primary receptors, and partly conditioned, involving other receptors of smell and sight, etc.—as substitutes for the taste-buds.

Isolating a small part of the stomach, called the Pavlov pouch (Fig. 192), and leading this pouch to the external sur-

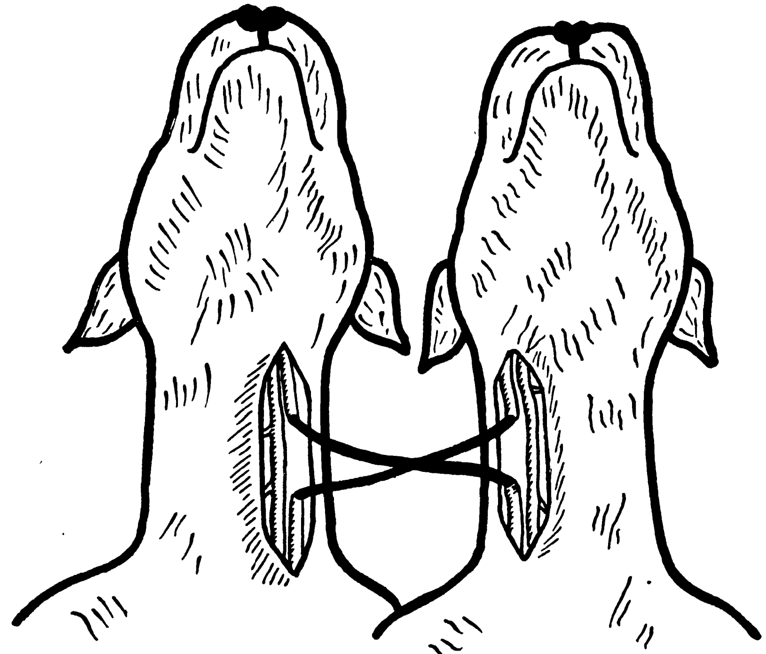
face of the abdominal wall, permitted Pavlov to observe the flow of gastric juice under a variety of conditions. Introducing food directly into the stomach—without allowing the animal to taste, smell, or see the food—calls forth about half of the normal production of the gastric juice. This flow of juice, which results from the mere presence of food in the stomach, is controlled only partially by a reflex mechanism. Cutting all the gastric nerves reduces but does not abolish this fraction. Accordingly it may be concluded that part of the production of gastric juice is controlled by some other mechanism; and this proved to be the hormone *gastrin.*

Gastrin is formed in the mucosa of the pyloric part of the stomach, and is discharged into the blood stream whenever the semi-digested food mass comes into contact with this mucosa. If an extract of the pyloric mucosa is prepared and injected into the blood, the gastric glands begin to secrete shortly after the injection. Complete proof of a hormonal agency in normal gastric secretion depends, however, upon cross-circulation experiments. The Pavlov pouch remains in continuity with the other parts of the stomach, and so it is not certain that all the nerves to the pouch can be cut. But if the blood streams of two dogs (A and B) are connected artificially, by mutual junction established between the major arteries (Fig. 193), any substance present in the blood of dog A must sooner or later be carried over into the blood of dog B. In this case there is no possibility that nerve connections exist between the organs of the two animals. Nevertheless, when food is placed in the pyloric stomach of dog A, the gastric glands of dog B—as well as those of A—begin to secrete, after a short lag. This secretion must be effected by some substance carried by the blood, and this hormone is called *gastrin.*

Some flow of gastric juice continues after the stomach is emptied—i.e., while the digesting food is passing through the first part of the small intestine; but this activity of the gastric glands has not been studied adequately. Possibly amino acids, sugars, and other products of digestion, which begin to be absorbed into the blood from the small intestine, exert an influe-

ence upon the gastric glands; or perhaps this final flow depends upon a reflex or a hormone which has not yet been recognized.

The Churning Movements of the Stomach. Each meal remains in the stomach until it has been thoroughly *liquefied*



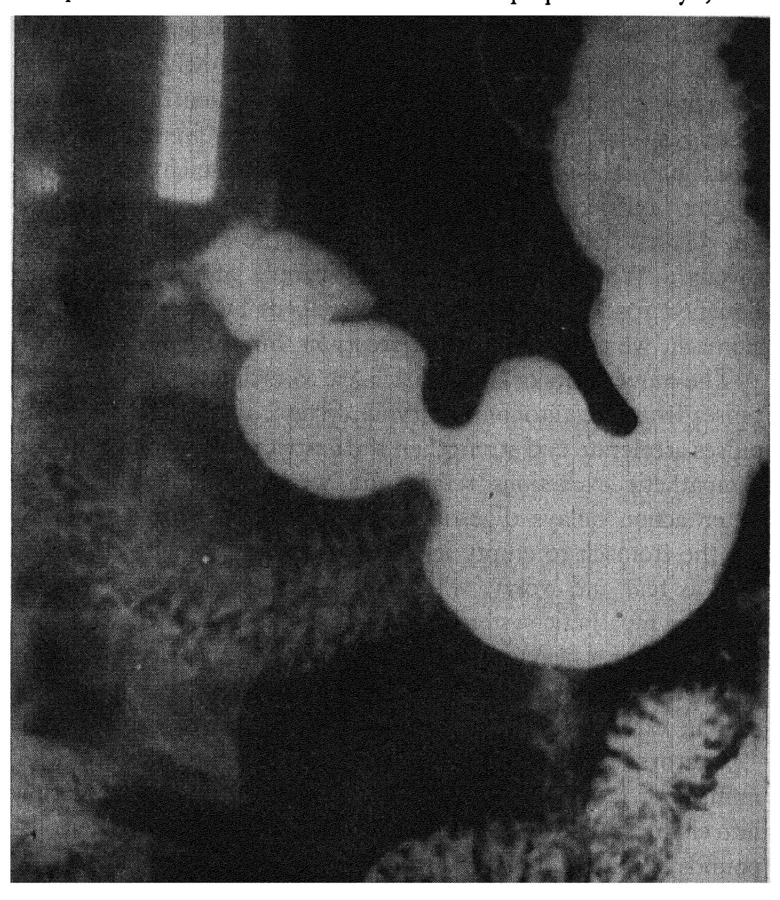
Reproduced by permission from *The Body Functions*, by R. W. Gerard, published by John Wiley and Sons, Inc.

FIG. 193.—By connecting the neck arteries (carotids) of two dogs with rubber tubing, as shown, the blood flows through both animals alike in the course of its travels. Such "cross-circulation" experiments are especially useful in demonstrating control of body activity by chemicals circulating in the blood stream. (Drawn by P. McC.)

and converted into a smooth thick fluid, called the *chyme*. Chyme has the consistency of a heavy cream soup; and the transformation of the ingested food mass into chyme depends partly upon the chemical properties of the gastric juice and partly upon mechanical changes induced by the churning action of the gastric musculature.

The churning movements are confined mainly to the pyloric part of the stomach, as is shown in X-ray photographs of the

stomach during the digestion of a *barium meal.* The barium compounds mixed with such a meal are opaque to X-rays; and



Courtesy Roentology Staff, Billings Hospital. Reproduced by permission from *The Body Functions,* by R. W. Gerard, published by John Wiley and Sons, Inc.

FIG. 194.—X-ray photo showing contraction waves in the human stomach. Barium sulfate taken recently in some milk has made the stomach contents visible in the photo. A metal rod marks the position of the backbone.

the barium-laden chyme throws a shadow, outlining the stomach contents on the photographic plate (Fig. 194). Thus it may be seen that during active digestion, the *body* of the stomach remains more or less passive, although gradually the body shrinks

as it slowly passes its contents into the actively churning "pyloric mill."

Essentially the churning of the pyloris represents a series of regularly recurrent peristaltic waves which sweep toward the pyloric valve. However, this valve remains tightly closed until the chyme is thoroughly liquid; and consequently the waves merely sweep the food mass back and forth in the "pyloric mill," until the valve begins to open. When the chyme is thoroughly liquefied, the pyloric valve begins to open periodically (p. 381), allowing small quantities of the chyme to squeeze through. When this occurs, a new sample of less thoroughly liquefied food is passed on to the pylorus by the body of the stomach, which thus acts as a reservoir for the "pyloric mill."

The movements of the stomach are co-ordinated by nerve impulses from the autonomic nervous system. Parasympathetic impulses accelerate and strengthen the gastric contractions, whereas sympathetic excitations retard and weaken the motility. The latter action delays digestion and prolongs the time required for the stomach to empty itself. Consequently emotional states, such as fear and worry, which involve a generalized excitation of the sympathetic system, are to be avoided, particularly during and after a heavy meal. For some reason, fat-rich meals are emptied from the stomach very slowly, whereas meals especially rich in carbohydrates are evacuated more rapidly than usual.

Factors Involved in the Liquefaction of the Meal. A number of factors tend to liquefy the food mass and convert it into chyme, while a meal remains in the stomach. Insoluble compounds in the food are transformed to soluble compounds; the ptyalin of the saliva continues to hydrolyze starch into maltose, especially in the interior of each bolus, before the HCl of the gastric juice permeates the mass; and pepsin begins to convert the proteins to proteoses and peptones as soon as the food mass is thoroughly acidified. Moreover, considerable water, in the form of saliva and gastric juice, is added to the meal, and this water increases the general fluidity, in addition to exerting a solvent action upon soluble compounds as they are produced during digestion. Also the gastric contents are gradually warmed by

body heat, which accelerates all chemical reactions and promotes solution. Moreover, this heat melts the fatty components of the food, permitting them to be emulsified thoroughly, as the chyme is churned in the "pyloric mill."

Emptying of the Stomach. When the strongly acid chyme is thoroughly liquid, it is squirted, about a teaspoonful at a time, through the pyloric valve into the first part of the small intestine. In fact, the pyloric valve begins to relax, allowing some of the chyme to pass as soon as the content of the mill reaches the proper consistency. The relaxing of the valve appears to be under reflex control, but the receptors and the nervous pathway of this reflex have been difficult to determine precisely.

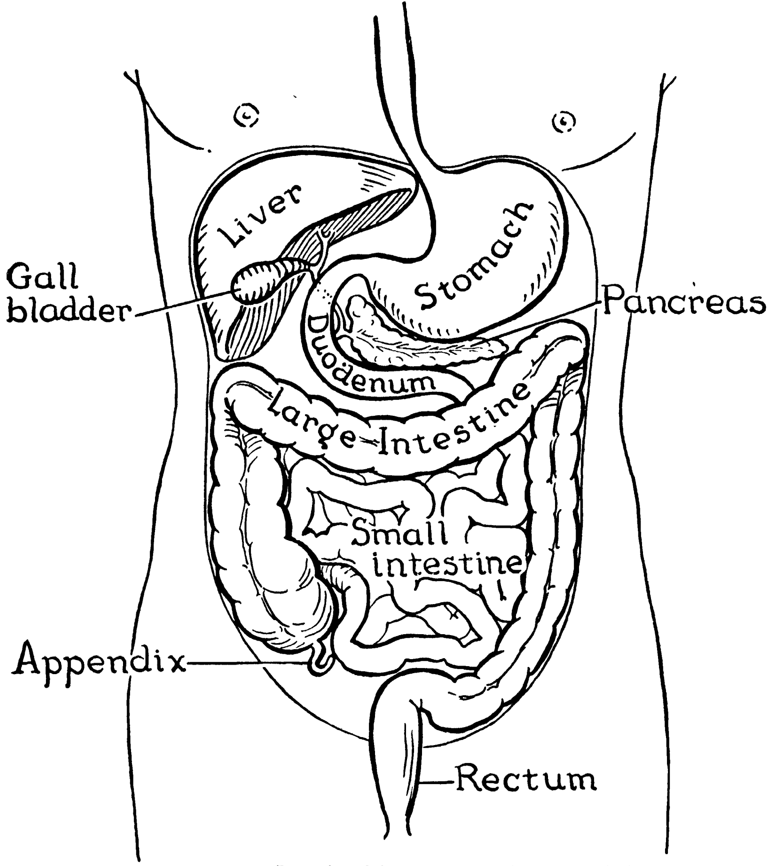
The Small Intestine. The great length of the small intestine (Fig. 195) is an index of its importance; and in fact the small intestine completes the *digestion* of every type of food, and is the site of the *absorption* of all the end-products of digestion.

All types of glands pour their juices into the small intestine. The intestinal mucosa is dotted throughout with numerous *unicellular* mucous glands; and there is a prodigious number of *simple* tubular glands, the *intestinal glands*, present in the wall of the intestine. But even more important are two large glands, the *liver* and the *pancreas*, which send their juices into the first part of the small intestine, near its origin from the stomach.

The great absorptive capacity of the small intestine depends partly upon the fact that it is more than 23 feet long, and partly upon the fact that its internal surface is greatly augmented by the presence of a large number of hairlike structures, the intestinal *villi*. In fact the internal lining of some parts of the intestine have the appearance of velvet; and each hair, or villus, of this lining extends inward, making contact with the chyme as it passes along the tube (Fig. 196).

On the basis of small differences of structure the small intestine is subdivided into three parts. The first part, the *duodenum*, is only about 10 inches long; but the duodenum is important

because it receives the *bile* from the liver, and the *pancreatic juice* from the pancreas (Fig. 190). Unlike the other coils of the small intestine, the duodenum occupies a fixed position in



Reproduced by permission from *The Body Functions*, by R. W. Gerard, published by John Wiley and Sons, Inc.

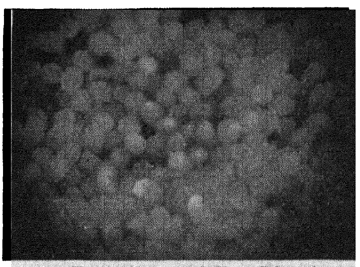
FIG. 195.—The digestive tract of man, in situ.

the abdominal cavity, because it is attached directly to the dorsal body wall. All other parts of the small gut, in contrast, enjoy some freedom of movement, because they are suspended to the dorsal body wall by a thin, transparent, sheetlike membrane, the *mesentery*. This mesentery provides a connection between the

intestine and the body wall, through which nerves and blood vessels pass to and from these otherwise isolated parts.

The second and third part of the small intestine are, respectively, the *jejunum* and the *ileum*. The jejunum is about 10 feet in length, and displays a greater number of the intestinal glands and a lesser number of villi than the ileum. The ileum terminates abruptly in the lower right region of the abdominal cavity, at which point it joins the *large intestine* (Fig. 195).

Relations of the Duodenum to the Liver and Pancreas. Each small sample of the chyme passes from the stomach into the duodenum, whereupon it immediately encounters a copious flow of both the pancreatic juice and the bile. These two juices flow into the duodenum together, because the bile duct and pancreatic duct join each other, forming a short common duct which penetrates the duodenal wall (Fig. 190).



From the sound film, *Digestion of Foods*, Encyclopaedia Britannica Films, Inc.

FIG. 196.—Magnified view of the inside surface of the small intestine showing the numerous villi.

The Pancreatic Juice. The *inorganic* components of the pancreatic juice are mainly water (about 98 per cent by weight), and various inorganic salts. Among these salts there is an unusually high concentration of the alkaline salt, sodium bicarbonate, which serves to neutralize the strongly acid chyme as soon as it leaves the stomach:

$$HCl + NaHCO_3 \rightarrow H_2O + CO_2 + NaCl$$

This function is important because all the digestive enzymes which act upon foods in the small intestine require a neutral or slightly alkaline medium for optimal activity.

Three enzymes are present in the pancreatic juice, namely: (1) *trypsin*, or pancreatic protease; (2) *amylopsin*, or pancreatic amylase; and (3) *steapsin*, or pancreatic lipase. *Trypsin* has great potency in the middle stages of protein digestion, i.e.

in the hydrolysis of proteoses and peptones to peptids, although native proteins, such as may escape peptic digestion in small quantities, are also digested by trypsin. Most of the peptids produced as a result of tryptic digestion are long-chain *polypeptids*, which contain more than four constituent amino acids; although *tetrapeptids* (with 4 amino acids), *tripeptids*, and even some *dipeptids* are represented. Thus the main reaction fostered by trypsin is:

$$1 \text{ mol.} \left\{ \begin{matrix} \text{proteoses} \\ \text{or} \\ \text{peptones} \end{matrix} \right\} + x \text{ mols. } H_2O \xrightarrow[\text{alk. med.}]{\text{trypsin}} x \text{ mols. peptids}$$

As collected directly from the pancreatic duct, the pancreatic juice contains an inactive form of trypsin, called *trypsinogen*, but the trypsinogen is transformed into trypsin as soon as the pancreatic juice comes into contact with the *intestinal* juice, which contains a suitable concentration of *ionic calcium*. Moreover, an optimal activity of trypsin is displayed in alkaline medium (pH 8.5).

Amylopsin plays a very significant role in the digestion of the starchy components of our foods—because amylopsin is afforded more time than ptyalin to act upon these compounds, and because amylopsin works more rapidly than ptyalin. As in the case of ptyalin, the end-product of starch digestion by amylopsin is maltose.

Steapsin is the only truly active lipase in the whole gastro-intestinal tract, and in the absence of a proper flow of pancreatic juice, much of the fat in a meal remains undigested and is egested with the faeces. The normal hydrolysis of fat:

$$1 \text{ mol. fat} + 3 \text{ mols. water} \xrightarrow[\text{alk. med.}]{\text{steapsin}} 1 \text{ mol. glycerol} + 3 \text{ mols. fatty acid}$$

is necessary to convert the fatty components of the food to end-products which can be absorbed and utilized by the body.

The Liver. In vertebrates generally, the liver is a comparatively huge organ; and in man the liver occupies the whole upper part of the abdominal cavity, just below the *diaphragm*

(Fig. 190). In fact the dome-shaped diaphragm, which separates the abdominal and thoracic cavities, arches directly over the liver, coming into contact with a considerable area on the upper hepatic surface.

The formation of bile is only one of the many functions of the liver (see p. 427). The bile is formed in all parts of the liver, and is drained into a system of fine ducts which permeate the whole organ. These hepatic ducts lead the bile to a main duct; but instead of flowing directly to the duodenum, the bile back-flows into the *gall bladder*, where it is stored until needed (Fig. 190). Then later, during the digestion of a meal, the muscular wall of the gall bladder contracts, forcing a stream of bile down the *common bile duct*, through which the bile enters the small intestine, together with the pancreatic juice. While the bile is stored in the gall bladder, however, part of its water content is absorbed by the walls of the bladder, so that bile collected from the bladder is more concentrated compared to the bile which comes directly from the liver.

The Bile. Although it contains *no enzymes*, bile plays a very important role in normal digestion. The inorganic components are relatively unimportant, although the sodium bicarbonate of the bile augments the neutralizing capacity of the pancreatic juice. And among the main organic components of bile, which include (1) the *bile salts*, (2) the *bile pigments*, and (3) *cholesterol*—only the bile salts are related to digestion.

Man's bile has a deep yellow-orange color; but the bile of other vertebrates is colored various shades of green, yellow, orange, or red, depending upon the proportion of *bile pigments* represented in each case. The main bile pigments are a red compound, *bilirubin*, and a green one, *biliverdin;* and both these pigments are decomposition products derived from *hemoglobin.* As the red blood cells of the body gradually disintegrate and are replaced by new ones, the hemoglobin gives rise to the bile pigments by a process which involves the splitting off of iron (Fe) and protein (globin) from each hemoglobin molecule. The bile pigments are carried in the blood stream to the liver, where they are *excreted* via the bile into the intestine. In the

digestive tract, the bile pigments suffer further chemical change whereby the color darkens to brown or black, and the color of the normal stools, or faeces, is derived mainly from the bile pigments. Thus when the flow of bile is stopped, as by a gall stone, or a catarrhal condition in the bile duct, the condition is indicated by the occurrence of a whitish, or "clay-colored" stool. Moreover, if the bile pigments accumulate sufficiently in the blood and tissues, the skin of the patient shows a yellowish or *jaundiced* appearance, which confirms the diagnosis that the bile pigments are not being excreted properly.

The importance of the *bile salts* is related mainly to the *digestion and absorption of fats.* The bile salts are *organic* compounds which act as emulsifying agents, so that the churning movements of the intestine are effective in producing a fine emulsion from the fatty components of the chyme. In such an emulsified state, the fats display a maximum of exposed surface at which the pancreatic lipase can act with high efficiency. Moreover, the bile salts appear to serve as *specific activators* of steapsin.

In the absence of bile salts—i.e., when the flow of bile is stopped—the *absorption,* as well as the digestion of fatty foods, is seriously impaired; and a considerable proportion of fatty foods is lost to the body in the faeces. The bile salts appear to augment the solubility of the fatty acids in the chyme, and this affects the absorbability of the fatty acids. Moreover, the bile salts are carefully conserved by the body. In fact, the bile salts themselves are absorbed in the lower parts of the small intestine, and are carried back to the liver, which re-secretes them into the bile. This regular *circulation of the bile salts* has been known for many years, although its significance was realized only in comparatively recent times.

The presence of *cholesterol* in bile is important from a clinical point of view. In certain cases, cholesterol precipitates from the bile, forming the commonest type of *gall stones.* The precipitation of such a "stone" occurs in the gall bladder, while the bile is undergoing concentration, although stoppage of the bile flow occurs only when a stone finds its way into the bile duct.

One factor conducive to such gall stones appears to be a lowered reserve of bile salts, since these compounds have a detergent action upon cholesterol and help to keep it in solution.

The Flow of Bile and Pancreatic Juice. Cutting the nerves to the gall bladder and pancreas abolishes less than half the normal flow of the secretions. Moreover, intravenous injections of extracts of the duodenal mucosa are followed by a copious flow of the juices, even after all nerves to the glands are cut. These and other experiments indicate that a hormonal control predominates for both the gall bladder and the pancreas; and in fact, two distinct hormones are involved: (1) *cholecystokinin*, for the gall bladder; and (2) *secretin* for the pancreas.

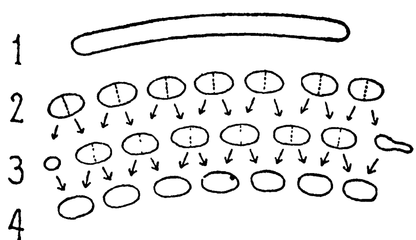
In the normal course of events, both secretin and cholecystokinin are liberated by the mucosa cells of the duodenum as soon as chyme flows from the stomach into the duodenum. The hormones pass in the blood stream to all parts of the body; but only the gall bladder is stimulated by cholecystokinin; and only the pancreas is activated by secretin.

The Intestinal Juice. The final stages of digestion proceed in the jejunum and upper coils of the ileum under the auspices of the enzymes of the intestinal juice—of which there are at least four. *Erepsin* is a peptidase, which completes the hydrolysis of the various peptids into amino acids; and *maltase, sucrase and lactase*, act respectively on maltose, sucrose and lactose, hydrolyzing these disaccharides into their monosaccharide constituents (p. 100). Recent reports indicate some lipase activity in the intestinal juice; but the potency is not very significant. The intestinal juice also contains sodium bicarbonate, which maintains a slightly alkaline reaction in the intestinal chyme, fostering a maximal activity of the intestinal enzymes.

By the time the chyme reaches the lower coils of the small intestine, practically all digestion is finished and absorption is proceeding apace. At the end-point of digestion the various foodstuffs are entirely converted to readily absorbable compounds; the proteins to amino acids; the carbohydrates to monosaccharides; and the fats to glycerol and fatty acids.

Movements of the Small Intestine. Some 5 to 10 hours are usually required for the transmission of a meal through the small intestine. During this time the chyme is gently churned and gradually moved from coil to coil along the length of the small gut.

The *churning* movements of the small intestine, as revealed by X-ray studies, are of two types—called: (1) *segmental* movements and (2) *pendular* movements. The segmental type of



From Best and Taylor, *The Living Body*

Fig. 197.—Diagram showing the effect of the *segmenting movements* upon the food mass in the intestine. A series of constrictions of the bowel wall suddenly divides the column of food (1) into a number of segments (2). Each of the latter is bisected again the next instant, the adjacent halves fusing as in 3, and being redivided as in 4. The process is repeated over and over again until the food is thoroughly mixed. (After Cannon.)

movement (Fig. 197), involves just one loop of the small bowel, which becomes constricted at regular intervals, dividing the chyme in the lumen into segments. Periodically the original constrictions fade and an equal number of new ones appear, more or less precisely in between the positions of the old ones. These alternating constrictions and relaxations, which recur about 10 times per minute, may continue for some time, kneading the intestinal chyme and assuring a complete mixing of the chyme with the digestive juices.

Pendular movements, essentially, are gentle peristaltic waves which sweep *back* and *forth* without progressing beyond the limits of a single loop of the bowel; and pendular movements are likewise for mixing purposes.

To *move* the chyme forward toward the large intestine, there are two kinds of peristaltic movements: (1) ordinary *peristaltic*

waves (p. 369); and (2) *peristaltic rushes.* The waves are relatively slow (about 1 cm. per sec.), and transient, since they tend to fade away after traveling a meter along the bowel; but peristaltic rushes are faster (about 12 cm. per sec.), and they sweep the bowel for considerable distances, sometimes all the way from the duodenum to the colon.

The Colon, Rectum and Anus. The relations of the *colon,* or *large intestine,* to the other parts of the digestive tract are shown in Fig. 195. This figure also shows the positions of the subsidiary parts of the colon, which are: (1) the *caecum,* a large blind pocket, which hangs down below the point where the small bowel enters the large one; (2) the *vermiform appendix,* a small fingerlike outpocketing of caecum; (3) the *ascending colon,* which passes upwards on the right side of the abdominal cavity; (4) the *transverse colon,* which slants diagonally across the abdomen, from the right to left; and (5) the *descending colon,* which passes downward toward the rectum, on the left side of the body. Just prior to the point where the large intestine joins the *rectum,* the descending colon displays a marked bend, the *sigmoid flexure.* One muscular valve, the *ileocaecal sphincter,* guards the opening of the ileum into the caecal portion of the large intestine; and two valves, the *anal sphincters,* close off the anal passage except when egestion occurs.

When the residual food mass reaches the colon, most organic compounds, as well as considerable quantities of water, have been absorbed (p. 426). However, the mass is still very fluid when it reaches the ileocaecal valve—where it tends to accumulate, pending one of the periodic peristaltic rushes which sweeps the material into the colon. This fluidity is not surprising, when it is realized that the quantity of water absorbed from the food mass while it passes through the small intestine is just about counterbalanced by the water content of the digestive juices which are secreted into the small intestine.

The main function of the colon, aside from conducting the residual food mass to the rectum and anus, is to *absorb water* from the mass, conserving this water for the use of the body. Aquatic vertebrates, in which water conservation is not a serious

problem, do not possess a very well-developed colon; but in terrestrial forms, the colon is conspicuous. The contents of the large bowel move very slowly, and usually about 12-14 hours are required for a given sample of the food mass to traverse the colon. Thus time is allowed for water absorption; and usually the faecal mass, when it reaches the descending colon, displays a plastic semi-solid consistency.

This lag in the passage of the food residues through the colon accounts for the very large growth of bacteria which is always found in the large intestine. In fact these bacteria usurp as much as 50 per cent of the dry weight of the normal stools. The colonic bacteria thrive—under ideal conditions of warmth, moisture, and darkness—upon such remnants of proteins, carbohydrates, and fats as may escape absorption in the small intestine. Ordinarily the bacteria inhabiting the colon are nonpathogenic; i.e., these bacteria are neutral parasites for which man has been a host for many centuries.

The proteolytic, or putrefactive, bacteria of the colon produce a variety of nitrogenous compounds in the course of their digestive and metabolic activities; and some of these products are highly toxic and odoriferous. Formerly it was thought that these nitrogenous compounds might be responsible for the unpleasant symptoms of "auto-intoxication"; but more recent studies indicate that these substances do not ever reach toxic concentrations in the general circulation (see p. 432).

Movements of the Large Intestine. Two types of colonic movement have been described: (1) feeble, sluggish *peristaltic waves,* which gradually advance the food residue through the ascending and transverse loops; and (2) vigorous *peristaltic rushes,* which periodically evacuate the transverse and descending loops into the rectum. Ordinarily the rectum remains empty of faeces until a few moments before *defecation* is to occur.

The various movements of the large and small bowels are coordinated by autonomic reflexes (p. 602). Peristaltic waves may be initiated by any local distention of the gut—as by an accumulation of the digesting food mass, or by artificially stretching

the wall by the inflation of a rubber balloon placed in the lumen. A particularly vigorous peristaltic rush, involving a large part of the small intestine, as well as the transverse and descending loops of the large intestine, frequently accompanies the ingestion of a new meal. This reflex, which is called the *gastrocolic reflex*, sweeps the food remnants from the colon into the rectum. In fact, this filling of the rectum normally generates the "desire to defecate," which tends to follow certain meals, according to the habits of the individual. The headache and other discomfitures of "constipation" appear to be associated with a prolonged and unnatural distention of the rectum by packed faeces. All the symptoms of the condition can be duplicated in man by merely packing the rectum with an inert mass, such as sterile cotton. This indicates that the discomfiture arises not from toxins absorbed from the gut, but from reflex effects upon the nervous system.

Different cathartics initiate mass movements, i.e., vigorous and enduring peristaltic rushes in the small and large intestines in various ways. Certain drugs (e.g., castor oil) strongly irritate the nerve endings in the mucosa of the tract, and these nerve endings are the receptors of the powerful reflex movements which follow. Salts (e.g., magnesium sulfate) have a double action. In the high concentrations used, they irritate the gastro-intestinal receptors; but more important still, a *hypertonic* solution of such a relatively non-absorbable salt tends to hold water in the digestive tract, keeping the food mass abnormally fluid even after it passes through the colon. The third type of cathartic (e.g., drugs such as cascara) act upon the reflex centers in the central nervous system (medulla), sensitizing these centers to discharge motor impulses to the musculature of the intestinal tract.

Regular use of any type of cathartic is to be avoided, because all types are to some extent habit-forming and at least slightly deleterious to the normal digestive and absorptive functions. In almost all cases constipation can be avoided by regularizing the defecation habit, bringing it into synchrony with the normal

autonomic reflexes of the gastro-intestinal tract; and in rare cases when this procedure is ineffective, a qualified physician should be consulted.

TEST QUESTIONS

1. Gastric vacuoles, which are characteristic of unicellular animals generally, have persisted among primitive multicellular animals. Explain, citing at least two specific examples.
2. Describe the processes of ingestion and digestion as they occur in Hydra.
3. Tubular digestive tracts tend to display more differentiation than saccular tracts. Explain this statement, basing the discussion on the digestive tracts of Hydra and the earthworm.
4. Explain the importance of the coelomic cavity in relation to the "digestive movements" of an animal.
5. Diagram the digestive tract of man, showing the connections of the various digestive glands.
6. Describe the general similarity of histological structure which is found in different parts of man's digestive tract.
7. Identify and locate: (a) the hard palate, (b) the uvula, (c) goblet cells, (d) the gastric glands, (e) the intestinal glands, (f) placoid scales, and (g) the parotid glands.
8. Briefly discuss man's dentition in relation to the teeth of other Mammals, especially the rodents, herbivores and carnivores.
9. Briefly explain the functions of each juice in terms of its *composition:*
   a. the saliva;
   b. the gastric juice;
   c. the pancreatic juice;
   d. the bile;
   e. the intestinal juice.
10. Assume that a man has eaten a bowl of rice, served with sugar and milk. Make a table to show the complete digestion of the *carbohydrate* components of this meal. Be sure to specify:
    a. all the different carbohydrates present in the meal;
    b. the enzyme or enzymes involved in the digestion of each compound;
    c. the glandular source of each enzyme;

d. the end products produced by digestion;
e. the part of the digestive tract in which the digestion occurs.

11. Make similar tables assuming that the man has eaten:
    a. some olive oil;
    b. some boiled egg albumen (protein).
12. Make a labelled diagram showing the connections of the human pharynx; discuss these connections in relation to the swallowing reflexes.
13. Explain how the mechanisms controlling the flow of saliva and pancreatic juice are different.
14. Name three hormones which are important in controlling the flow of the digestive juices, and in each case specify:
    a. the site of production of the hormone;
    b. the gland (or other part) which is specifically activated by the hormone;
    c. The manner in which the hormone reaches the effector organ.
15. Plan an experiment which would prove that the pancreas is activated by a substance (or substances) which is carried in the blood stream.
16. Discuss the innervation of the stomach in relation to the gastric movements.
17. What is a sphincter valve? Specify four sphincters present in the gastro-intestinal tract of man; explain the different functions of these valves.
18. Describe the movements of the stomach in relation to:
    a. the churning of the chyme;
    b. the evacuation of the chyme from the stomach.
19. Explain how the early work of Spallanzani and Beaumont contributed to an understanding of the composition and functions of the gastric juice.
20. How did Pavlov prove that seeing, smelling, and tasting food elicit a flow of gastric juice even when the food doesn't reach the stomach? How is this part of the secretion effected?
21. What is rennin? What important role is played by rennin in the digestive processes of man and other *Mammals?*
22. Make a labelled diagram to show the essential relations of the duodenum to the stomach, pancreas, and liver.
23. The gastric chyme is highly acid, whereas the intestinal chyme is

definitely alkaline. Explain precisely where and how this transition is effected, and why it is important.

24. Explain the relation between:
    a. the blood pigments, bile pigments and faecal pigments;
    b. the bile pigments and jaundice;
    c. the "concentrating function" of the gall bladder and gall stones;
    d. gall stones and the bile salts.
25. Describe and explain the *circulation of the bile salts.*
26. Describe the movements of the small intestine and explain their significance.
27. Compare the movements of the small and large intestines.
28. Make a careful labelled diagram showing the relations of the colon to the ileum, caecum, appendix, rectum and anus.
29. Briefly discuss:
    a. the functions of the colon;
    b. the importance of the colonic bacteria.
30. What is the gastrocolic reflex and how is it related:
    a. to defecation;
    b. to the symptoms of "auto-intoxication"?
31. Specify three different kinds of cathartics and explain the mode of action of each.

FURTHER READINGS

1. *The Living Body,* by C. H. Best and N. B. Taylor; New York, 1944.
2. *The Body Functions,* by R. W. Gerard; New York, 1941.
3. *The Machinery of the Body,* by A. J. Carlson and V. Johnson; Chicago, 1937.

CHAPTER 16

THE CIRCULATORY SYSTEM

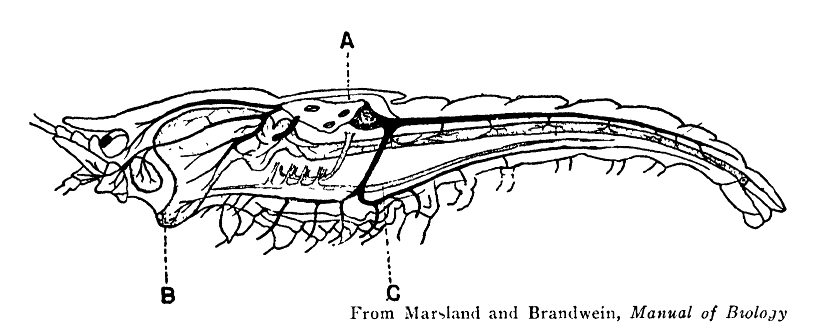
LARGE animals could not exist without an effective circulation. Foods from the digestive tract must pass quickly to all the cells of the body, and the respiratory gases must be transported between the various tissues and the breathing organs. Also metabolic wastes have to be collected and brought to the excretory organs; and hormones and other special substances must be distributed throughout the body without delay. Diffusion and osmosis alone are much too slow to fulfill these needs, except in very small and simple animals such as Hydra. Accordingly, all larger animals have developed one or more circulatory fluids, which are forcefully pumped throughout the body for the transportation of necessary substances.

Direct Circulations; Hemolymph. Some lower animals possess only one circulatory fluid; and this *hemolymph* performs the functions of both the blood and the lymph of higher forms. Hemolymph fills the tissue spaces, coming into contact with the cells; and thus the hemolymph carries materials *directly* to the cells.

Planaria and the other flatworms (p. 741) possess a very simple hemolymph system. The hemolymph of Planaria flows through the intercellular spaces which permeate the loosely packed mesodermal tissues. No heart is present to pump the body fluid; but the hemolymph flows irregularly back and forth throughout the body, as a result of the muscular movements of the worm. Such a slow and irregular flow suffices to distribute foods to the various tissues, because the gastro-vascular cavity of this animal sends branches to all parts. Also branches of the

excretory system reach all the tissues, so that the metabolic wastes are not carried very far before they are eliminated. Nor is the hemolymph very important in the respiration of Planaria. The animal is relatively small; and an exchange of gases between the cells and the surrounding water takes place quite rapidly by osmosis.

The hemolymph system of the lobster (p. 743) and other Arthropods (p. 743) is somewhat more complex. The heart of



From Marsland and Brandwein, *Manual of Biology*

FIG. 198.—Hemolymph circulation of the lobster, as shown in a diagrammatic longitudinal section. A, pericardial chamber, B, mouth; C, sternal sinus. (Other vessels described in text.)

the lobster is a hollow muscular sac, which lies in the *pericardial cavity*, surrounded by the hemolymph (Fig. 198). When the heart expands, it sucks in hemolymph through valved openings, the *ostia*, which penetrate the cardiac wall. Then, when the heart contracts, the ostial valves close, and the hemolymph is forced out through the arteries to the various parts of the body (Fig. 198). The arteries convey the hemolymph directly to the tissue spaces in each organ of the body. Some arteries go to the enteron and here the hemolymph passes through the channels in the gut wall, absorbing food substances as it flows. Large arteries also go to the excretory organs (*green glands*), and while the hemolymph filters through these organs, it gives up excretory wastes collected in all other parts of the body. In the muscles and other tissues of the body, the arteries bring the hemolymph into direct contact with the cells, and the hemo-

lymph provides the cells with food and oxygen and carries away the waste products of metabolism.

In returning to the heart the hemolymph of the lobster drains from the tissue spaces into the *sternal sinus* (Fig. 198), a large channel that leads to the gills. Then, in flowing through the gills, the hemolymph takes on oxygen from the water bathing the gills, and gives up carbon dioxide. Finally, the hemolymph passes via a pair of broad channels, the *branchio-pericardial* canals, back to the pericardial cavity, completing the circuit.

Indirect (Blood-lymph) Circulations. The disadvantage of such *direct* types of circulation is the relatively slow rate of flow. Inevitably the flow is slow because the hemolymph must be forced through irregular tissue spaces, where it encounters large resistance. This difficulty has been circumvented in higher animals by the evolution of two circulatory fluids: the *blood* and the *lymph*. In vertebrates, for example, the lymph flows slowly through the tissue spaces; but the blood flows at high speed through well-defined pipelike blood vessels.

In such *indirect* types of circulation, substances in the blood can reach a tissue cell only indirectly—by passing by osmosis through the wall of a capillary and diffusing through the lymph to the cell in question. However, each tissue of the body is very thoroughly permeated by blood capillaries to such an extent that the total area of the capillaries in our muscles alone measures more than 5,000 square meters. The very rapid flow of blood and the almost instantaneous osmotic equilibrium which takes place between the blood and lymph in the capillaries all over the body, enables the *vertebrate circulatory system* to cope with the distribution problems of the largest and most active animals in existence.

Blood. If mammalian blood is prevented from clotting, it will settle on standing, forming two main layers. The upper straw-colored layer is the fluid *plasma*, which accounts for about 55 per cent of the blood volume; and the dark-red lower layer is a densely packed mass of cells—the *corpuscles*.

The Plasma. The plasma serves not only as a vehicle for the blood corpuscles; but also it transports a wide variety of

substances in solution (see Table XIII). Some of these substances—e.g., foods and metabolic wastes—enter and leave the blood stream in the different parts of the system; but others—such as proteins—remain in the plasma quite indefinitely. One of the proteins, *fibrinogen*, plays an essential role in the clotting of blood (p. 402); and all the blood proteins probably help to maintain the osmotic properties of the plasma (p. 418).

TABLE XIII

MAIN COMPONENTS OF HUMAN BLOOD

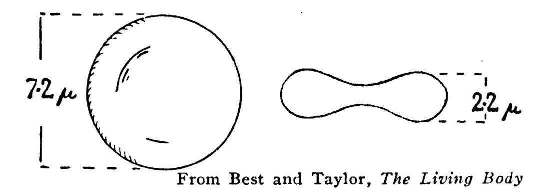
A. *Corpuscles*
1. Red corpuscles, or *erythrocytes*
2. White corpuscles, or *leucocytes*
3. Platelets, or *thrombocytes*

B. *Plasma*
1. Water (90%, by weight)
2. Inorganic salts (1%)
3. Major proteins, 7%: serum albumin, (4%), serum globulin (2.7%), fibrinogen (0.3%)
4. Other substances, 2%
   a. Absorbed foods (glucose, amino acids, glycerol, fatty acids, neutral fats and other lipids)
   b. Collected wastes (urea, uric acid and other compounds)
   c. Hormones, enzymes and antibodies
   d. Respiratory gases (oxygen and carbon dioxide)

Owing to the presence of *antibodies*, blood plasma is frequently able to neutralize specific poisons, such as the toxins produced by infecting bacteria and other parasites. If a small dose of rattlesnake venom is injected into a horse, for example, the plasma of the horse—after several days—is found to contain a specific antibody which is capable of neutralizing a much larger dose of this venom. Consequently serum from the treated horse can be used to save the life of human snake-bite victims. In general, the toxic product which elicits the production of an antibody is called an *antigen*; and virtually all *protein* compounds, providing they are foreign to the organism producing the antibody, are capable of acting as antigens. Antibodies are produced in various tissues of the body, but they are carried mainly in the blood plasma. A significant part of the organism's resistance to infectious diseases depends upon the production of

specific antibodies; and a lasting immunity to certain diseases indicates that some antibodies, once they have been formed, remain in the blood stream more or less indefinitely.

The Red Corpuscles. There are from four to six million red cells per cubic millimeter in the blood of normal human adults,

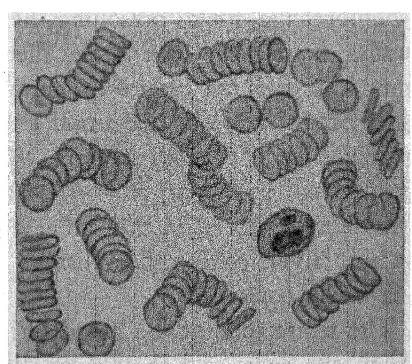


From Best and Taylor, *The Living Body*

Fig. 199.—Showing the diameter and thickness of a red blood cell.

although in males the count tends to run about a million higher than in females. Each individual erythrocyte is an extremely small biconcave disc with a pale pink color (Figs. 199 and 200); but collectively they account for the deep red color of the blood.

The chief function of the erythrocytes is to augment the oxy-



From Best and Taylor, *The Living Body*

Fig. 200.—A film of normal blood, illustrating the relative numbers of red and white cells. A field as large again as that shown would probably contain no other white cell.

gen-carrying capacity of the blood. About 50 per cent of the weight of an erythrocyte represents *hemoglobin*, a protein compound. Molecule for molecule, this iron-containing pigment forms a loose compound with oxygen, and consequently the quantity of oxygen carried in solution by the plasma is aug-

mented by the quantity of oxygen that unites chemically with the hemoglobin of the corpuscles.

A majority of vertebrates (fish, amphibia, reptiles and birds) possess erythrocytes with typical nuclei. But in man and other *Mammals*, the nuclei are lost by the cells before the erythrocytes are launched into the blood stream. Mammalian erythrocytes are able to survive in the circulation for only about 25-30 days—and then they go to pieces. Accordingly a constant replacement of red cells must go on, if *anemia* is to be avoided; and in fact several million new red cells are launched into the circulation during every *second* of a man's life. In adult man the formation of new red cells occurs in the *hemopoietic tissues* of *red bone marrow;* but in the embryo—and in lower vertebrates generally—erythrocytes are formed in the liver, spleen and lymph nodes (p. 419). A lowered content of hemoglobin in the blood—whether due to an abnormally rapid loss of erythrocytes, or to a defective replacement of the red cells—is called *anemia.* The anemia may be due to a variety of causes—such as hemorrhage, metal poisoning, hereditary fragility of the corpuscles, inadequate iron in the diet, and so forth. Inadequate dietary iron does not reduce the number of erythrocytes; but the individual red cells are small and pale—due to a lack of hemoglobin. In pernicious anemia, the body lacks a specific compound, called the *hematinic principal.* Normally this bone-marrow stimulant is stored in the liver; and the feeding or injecting of beef liver concentrates brings most cases of pernicious anemia under control.

Leucocytes. The white cells of the blood (Fig. 200) are far less numerous than the reds, and they normally total to only about 6,000-10,000 per cubic millimeter. All leucocytes have a colorless cytoplasm and definite nuclei. Leucocytes are of various kinds, as is shown in Table XIV; and some kinds are able to leave the blood stream through the capillary walls.

Phagocytosis: Another Defense Against Infection. Some leucocytes, particularly the neutrophils and monocytes, carry on an active defense against pathogenic bacteria—when these parasites manage to enter the tissues through an open wound.

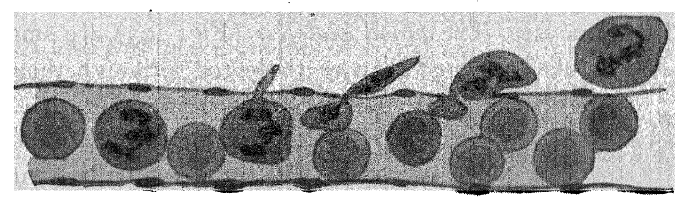
TABLE XIV

THE KINDS OF LEUCOCYTES IN MAN

A. *Granulocytes* (*polymorphonuclear leucocytes*); with distinct granules in the cytoplasm; nuclei conspicuously irregular and lobose, or even subdivided; originate from bone marrow:
   1. Neutrophils: granules stain with neutral dyes, or with mixtures of acid and basic dyes; nucleus, with many lobes; highly motile and phagocytic; very numerous, making up about 67% of the total white cell count.
   2. Basophils: granules stain with basic dyes (e.g., methylene blue); nucleus usually with two lobes; about 0.5% of total whites: non-phagocytic.
   3. Eosinophils: granules stain with acid dyes (e.g., eosin); bi-lobed nucleus; 3% of total white cell count; non-phagocytic.

B. *Agranulocytes* (*Lymphocytes*): cytoplasm, without granules; nucleus, rounded; originate from lymphoid tissues (lymph glands, spleen, etc.):
   1. Small lymphocytes: about 8 microns diameter; 25% of total whites.
   2. Large lymphocytes: about 11 microns; 3% of total whites.
   3. Monocytes: about 15 microns; actively amoeboid and *phagocytic;* 1.5% of total whites.

The leucocytes migrate toward the wound, passing out through the walls of the capillaries in the infected area by a process called *diapedesis* (Fig. 201). The white cells arrive in force at



From Best and Taylor, *The Living Body*

FIG. 201.—Diapedesis. A leucocyte shown at short intervals during its progress through the wall of a capillary.

the site of infection, and begin ingesting the bacteria in large numbers (Fig. 202). Also the leucocytes tend to surround the infected region and to prevent the bacteria from spreading. Many white cells succumb to toxins produced by the bacteria; and these dead leucocytes make up the chief component of *pus*, as it accumulates at the infection. Besides being able to digest the bacteria and other foreign particles which they have phagocytized, the leucocytes secrete enzymes extracellularly. These enzymes digest away the dead or dying (necrotic) tissues, espe-

cially near the external surface of the infection. Thus the leucocytes clear a channel to the exterior; and through this channel the pus and other contents of the *abscess* may finally be discharged.

The functions of the other leucocytes (lymphocytes, basophils, neutrophils and eosinophils) are not clearly understood;

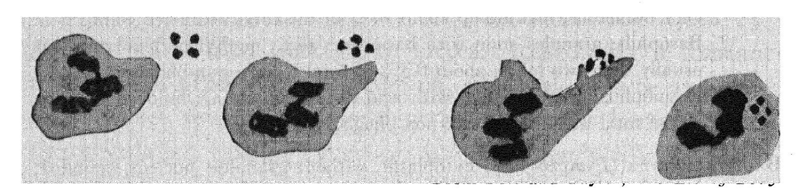
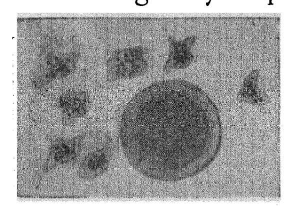


FIG. 202.—Drawing of a neutrophil at ½ minute intervals to show motility and phagocytosis. The dots represent a group of bacteria.

although probably they have some relationship to disease resistance. In different infections different kinds of leucocytes tend to accumulate in the blood, and consequently the physician must obtain a *differential white cell count*, in making a diagnosis of an unknown infection.

Thrombocytes. The *blood platelets* (Fig. 203) are smaller and less regularly shaped than erythrocytes, although they resemble erythrocytes in that they are very abundant (about 2.5 million per cu. mm.), and in that they lack nuclei. The thrombocytes are formed from the cytoplasm of certain very large cells in the bone marrow, by a process of fragmentation. Platelets cannot be seen in ordinary *shed* blood because they disintegrate immediately, liberating a substance which participates in clotting.



From Best and Taylor, *The Living Body*

FIG. 203.—Blood platelets, or thrombocytes. A red blood cell is shown for comparison of size.

Blood Coagulation. Victims of *hemophilia*—a rare hereditary defect of the blood—bleed very profusely even from the slightest wound. Hemophilic blood fails to clot in the normal time (5-6 min.), but takes an hour or more to coagulate. In

the absence of a normal clot to stop the bleeding, blood continues to flow from any ruptured vessel, and the life of the "bleeder" may be endangered.

The clotting of a sample of normal blood involves a series of chemical reactions which starts as soon as the blood comes into contact with a damaged tissue—or with some other foreign surface. The main reaction involves the conversion of the soluble protein, *fibrinogen*, into the insoluble protein, *fibrin*. The fibrin precipitates in the form of a sub-microscopic network of interlacing fibrils, which holds the other blood components within a colloidal mesh. At first the clot, or *thrombus*, is a semisolid mass with a gelatinous consistency. But in time the fibrin framework shrinks, squeezing a straw-colored fluid, the *serum*, to the surface of the clot, which now becomes hard and tough. The serum is almost totally lacking in fibrinogen and displays no further tendency to clot.

The fibrinogen → fibrin reaction depends upon a specific enzyme, *thrombase*. Thrombase itself is not present in the circulating blood, but blood contains an inactive precursor of the enzyme, which is called *prothrombase*. Prothrombase must be converted into thrombase before the blood can clot. In the absence of ionic calcium, prothrombase cannot be activated (except very slowly); and this accounts for the fact that coagulation does not occur when calcium-precipitating reagents (e.g., oxalate compounds) are added to the blood.

When the blood escapes the vessels and contacts a damaged tissue, there is liberated a substance, called *thromboplastin*. Thromboplastin is present in a wide variety of animal tissues, including the blood platelets. Thus when blood escapes the vessels, thromboplastin activates the prothrombase → thrombase reaction (very rapidly when ionic calcium is available); and as soon as thrombase becomes available, fibrinogen quickly precipitates as fibrin.

Although some factors still remain unknown, the foregoing account of coagulation is substantiated by a large accumulation of evidence. Both prothrombase and thrombase have been extracted from blood in highly active, dry form. Like other en-

zymes thrombase is readily destroyed by heat (50° C.), although the precursory protein, prothrombase, is much more heat stable. Thromboplastin, which normally initiates the clotting reactions, appears to come from two sources: (1) the cells of the damaged tissues; and (2) the blood platelets, which disintegrate, whenever blood comes into contact with a foreign surface—except when such a surface is exceedingly smooth. Thus if blood is drawn directly from a vein into a test-tube which has been coated internally with a film of oil, coagulation is delayed for an hour or more. In this case thromboplastin is lacking, since no contact with the damaged tissues has been allowed, and since the platelets fail to disintegrate in the usual fashion.

Anticoagulants. Anticoagulants are compounds which prevent, or definitely inhibit, blood clotting. Citrate, fluoride and oxalate salts all have the common property of removing ionic calcium from the blood; and these anticoagulants are used very commonly in handling blood for routine analysis. Blood-sucking creatures, such as leeches, produce organic anticoagulants. Typically these reagents inactivate thrombase, as is the case for *hirudin*, the anticoagulant of the leech. In normal circulating blood there appears to be a similar unidentified anticoagulant, but this is neutralized by thromboplastin when coagulation occurs. Also a very powerful anticoagulant, *heparin*, can be extracted from liver and muscle tissues. Heparin inactivates thrombase, and is used in surgical cases to prevent intravascular clotting (thrombosis), which sometimes occurs in post-operative patients. The reluctant clotting of hemophilic blood does not appear to be due to the action of any anticoagulant. In fact the causes of hemophilia are still obscure, although one factor seems to be an abnormally great stability of the thrombocytes. In hemophilic blood, the thrombocytes are slow to disintegrate, and this limits the available supply of thromboplastin.

The Vertebrate Heart. Embryologically the vertebrate heart represents a highly modified blood vessel with thick contractile walls. In man and other vertebrates, this special vessel develops in the mid-ventral region of the embryo, just behind the gill slits. The embryonic heart soon differentiates into two

muscular chambers—the *auricle* and *ventricle*—which then begin to pulsate rhythmically (Fig. 204).

The auricle has a thinner wall than the ventricle. Each time it relaxes, the auricle collects blood from the *sinus venosus* (Fig. 204); and when it is filled, the auricle contracts, forcing the blood into the ventricle. Then the thick-walled ventricle contracts—forcing the blood to flow at high pressure, out into the arteries of the body. Valves—situated at the entrance and exit

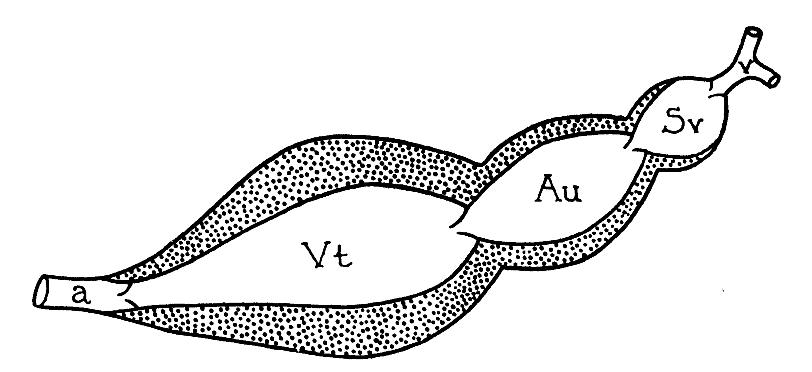


FIG. 204.—An early stage in the development of the heart. Au, auricle; Vt, ventricle; a, aorta; Sv, sinus venosus; v, large veins, which bring blood to heart.

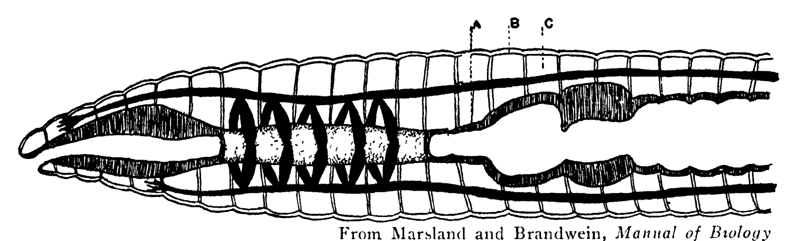
points of the auricle and ventricle—prevent any appreciable backflow; and practically all the force of the contracting heart goes to the propulsion of the blood in a forward direction.

The simple *two-chambered* heart of the early *embryo* is essentially similar to the fully developed heart of *lower* (fish-like) *vertebrates*, in which *gills* serve as the respiratory organs. Lung-breathing vertebrates, however, except for the Amphibia, have developed a *four-chambered heart*, with a separate auricle and ventricle to pump blood through the lungs (p. 413). Regardless of type, however, the heart is essentially a hollow muscular chamber which contracts repeatedly, forcing the blood to circulate.

More primitive organisms may lack a definite heart, or strictly localized pumping organ. The earthworm, for example, possesses a *dorsal blood vessel*, which is contractile all throughout

the length of the body (Fig. 205). This elongate blood vessel, together with the five pairs of vessels which encircle the esophagus of the earthworm (Fig. 205), maintains a steady series of contractions which propel the blood. The flow is entirely in one direction, due to the presence of numerous valves in the blood vessels.

The Blood Vessels. The blood vessels of an adult vertebrate are defined in relation to the heart: i.e., *arteries* lead *away* from

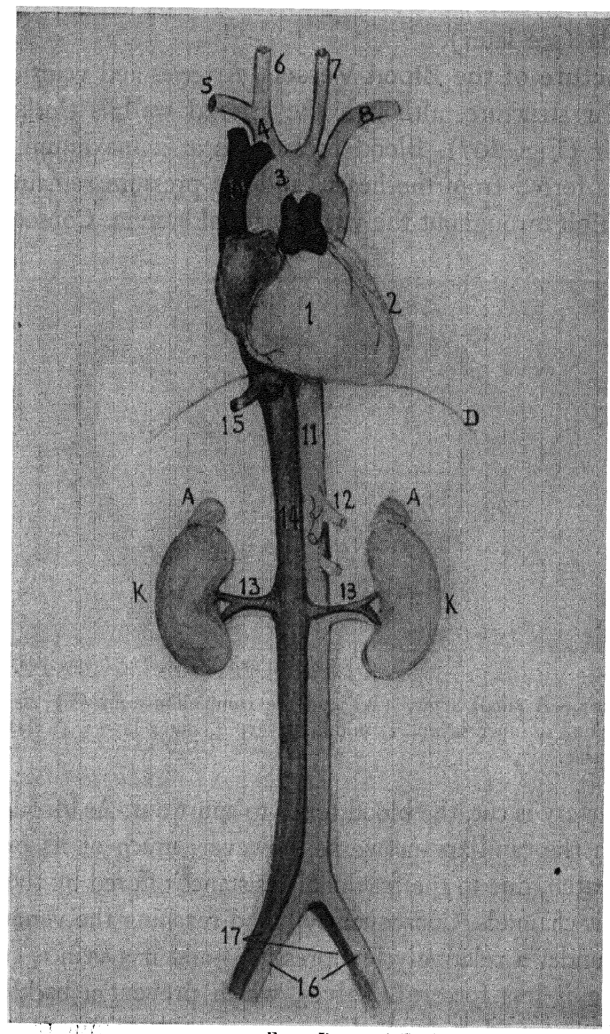


From Marsland and Brandwein, *Manual of Biology*

FIG. 205.—The main blood vessels of the earthworm. The dorsal vessel runs above the digestive tract; the ventral vessel is below the digestive tract; and the five pairs of aortic loops encircle the esophagus. A, wall of digestive tract; B, body wall; C, coelom.

the heart; *veins lead toward* the heart; and *capillary networks* connect the arteries with the veins.

In man there are two arterial systems: (1) the *pulmonary system,* which carries blood from the *right ventricle to the lungs;* and (2) the *systemic system,* which leads from the *left ventricle* to all other organs in the body. The main trunk of the pulmonary system is the pulmonary artery (Fig. 206, 9), which sends a branch directly to each lung; and the main trunk of the systemic circuit is a very large artery, the *aorta,* which sends smaller branches to every part of the body, except the lungs (Fig. 206, 3 and 11). The artery to each organ ends in a capillary network which permeates all the tissues of that organ. The venous system begins as many small tributaries from the capillaries in the various organs—and terminates in the large veins, which enter the auricles (Fig. 206, 10 and 14). In general, the artery to a particular organ runs side by side with the vein from the same organ, so that the artery and vein are given corresponding names (e.g., renal arteries and renal veins, see

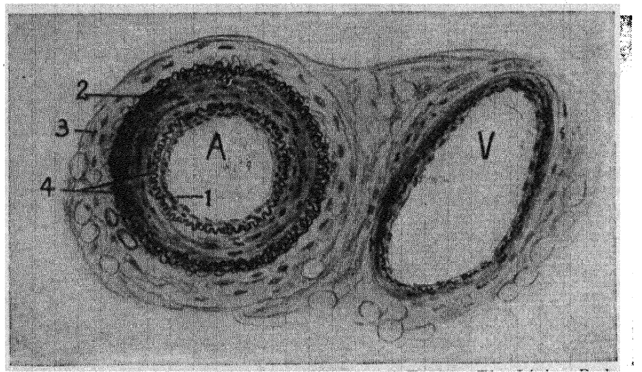


From Best and Taylor, *The Living Body*

FIG. 206.—Main vessels of the human body. Veins and pulmonary artery in darker shading. 1, right ventricle; 2, left ventricle; 3, arch of aorta; 4, innominate artery; 5, right subclavian artery; 6, right common carotid artery; 7, left common carotid artery; 8, left subclavian artery; 9, pulmonary artery; 10, superior vena cava; 11, abdominal aorta; 12, abdominal branches of aorta; 13, renal vein and artery; 14, inferior vena cava; 15, hepatic veins; 16, common iliac arteries; 17, common iliac veins; A, adrenal gland; D, diaphragm; K, kidney.

Fig. 206, 13). However, there are many exceptions to this general rule (see later).

Structure of the Blood Vessels. Arteries and veins display a similar structure, although the arterial wall is thicker and stronger (Fig. 207). Blood pressure is at a maximum as the blood is forced from the heart; and the pressure remains relatively high throughout the whole arterial system. Consequently



From Best and Taylor, *The Living Body*

FIG. 207.—A small artery (A) and the companion vein (V), as seen in cross-section. 1, inner layer; 2, middle layer; 3, outer layer; 4, elastic connective tissue.

if any artery is cut, the blood tends to spurt out. As blood passes through the capillary networks, however, much of its pressure is dissipated, due to the frictional resistance offered by these microscopic channels. Consequently blood reaching the venous system is under a relatively low pressure—and if a vein is cut, the bleeding is less forceful. Valves, which prevent a backflow of blood, are found at fairly frequent intervals within the veins, but not within the arteries.

The same *three layers of tissue* are present in the walls of an artery and vein, although these layers are thicker and more clearly defined in the artery. The *inner layer* (Fig. 207) is the *endothelium*, a smooth lining of squamous epithelial cells, arranged more or less like the stones of a pavement. This smooth endothelial lining offers a minimum resistance to the flow of blood through the vessels. The middle layer is a sheath of

visceral muscle, flanked both inside and out by *elastic connective tissue;* and the *outer layer* is composed of loose connective tissue. The fibers of the muscle sheath tend to encircle the artery—permitting the artery to change its caliber according to the needs of the tissues at the particular time. During exercise, for example, the arteries to the muscles and lungs dilate—thus providing a more abundant blood supply to these tissues during the period of extra activity.

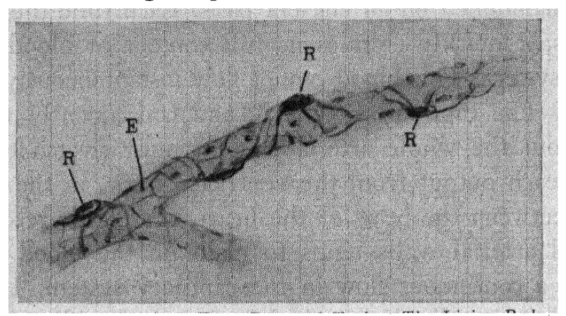
Unless the arterial walls were elastic, the circulation could not be maintained on an efficient basis. Each time the ventricle contracts, it quickly empties its full content of blood into the arterial system. This blood cannot flow instantaneously through the very fine capillary networks, and consequently the walls throughout the whole arterial system must stretch to accommodate each output from the ventricle. Then, in the short intervals between the beats of the heart, the elastic recoil of the stretched arterial walls tends to maintain the blood pressure, assuring a continuous flow in the capillary system. In feeling one's pulse, accordingly, one is detecting the rapidly alternating stretching and recoiling of the walls of one of the larger arteries.

Both the visceral muscle and the yellow connective tissue of the wall contribute to the elasticity of the arteries. With increasing age, however, the arteries tend to lose their natural resilience—partially because of a progressive calcification in the older tissues. When this occurs the blood pressure rises, since the heart works harder to maintain the circulation. Such a combination of rising blood pressure and more brittle arteries has serious consequences if an artery breaks and deprives a vital organ of its circulation.

The Capillary Circulation. The *aorta* sends branches to all parts of the body (except the lungs); and each organ receives at least one larger or smaller branch, depending on its size and activity. *In the organ,* a profuse branching occurs, and this branching permeates all the tissues. The initial branches, or *arterioles,* are like the main artery, except that they are smaller and have thinner walls. Gradually, however, the outer and middle tissue layers of the arteriole become thinner and thinner,

until finally only the naked endothelium remains—and this is the wall of a *capillary* (Fig. 208). The diameter of some of the capillaries is so small that the blood corpuscles must pass through in single file (Fig. 209). Also the capillary network is so extensive in every part of the body that one can scarcely suffer the slightest cut without drawing blood from the severed capillaries.

Eventually the capillaries throughout an organ begin to join each other, forming larger vessels, called *venules*. And the



From Best and Taylor, *The Living Body*

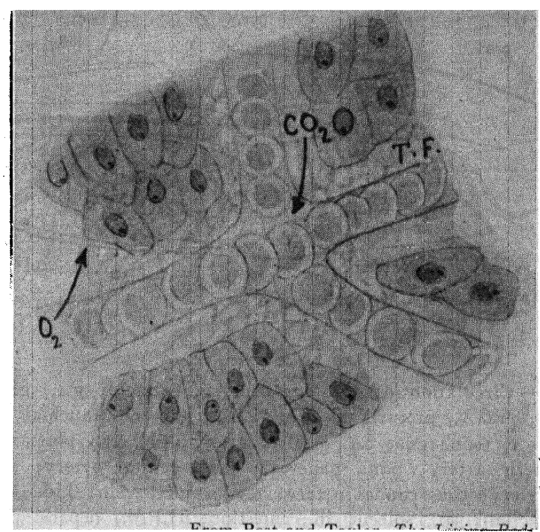
FIG. 208.—A capillary. E, endothelial wall; R, Rouget cells bordering the endothelial cells.

venules, in turn, become the tributaries of the one or more *veins*, which drain blood from the organ and return it to the heart.

Relationship Between the Blood, Lymph and Tissue Cells. As may be seen in Fig. 209, the blood in an organ does not come into direct contact with the tissue cells. Consequently material exchanges between the blood and the cells must involve a passage of substances through the capillary walls and across the lymph in the tissue spaces. Such osmotic exchanges go on rapidly and continuously only in the capillary parts of the blood system—where the walls are sufficiently thin.

The exchanges between capillary blood and the surrounding tissues of a working muscle are typical of such exchanges generally. Blood entering the muscle is well supplied with oxygen absorbed from the lungs, and with food compounds, absorbed from the gastro-intestinal tract. The muscle fibers, however,

contain very little of these substances, which are continually consumed in metabolism. Consequently oxygen, glucose and the other nutrients keep passing from the blood across the lymph and into the muscle fibers. Conversely carbon dioxide and the other metabolic wastes tend to reach a relatively high concentration in the fibers, where they are produced; and so the



From Best and Taylor, *The Living Body*

FIG. 209.—Illustrating internal respiration. Capillary shown filled with red cells; T.F., tissue fluid (lymph).

metabolic wastes keep passing from the fibers, through the lymph, and into the capillaries.

Single vs. Double Circulations. The circulatory system of man and other higher vertebrates is a highly modified and improved version of the circulation of the lower vertebrates. The general pattern of the circulation in primitive vertebrates is well illustrated by the dogfish (Fig. 210). The dogfish and other gill-breathing forms possess a relatively simple *two-chambered heart* which pumps the blood through just a *single* circuit; and in passing through this one circuit the blood performs all necessary functions.

As may be seen in Fig. 210, the *unaerated* (unshaded) blood

leaves the *ventricle* via a large arterial trunk, the ventral *aorta;* and there are five pairs of branches, the *aortic arches,* which surround the gill clefts and carry the blood to the *dorsal aorta.* Before reaching the dorsal aorta, however, the blood must flow through the capillaries of the *gills,* where the blood becomes aerated (shaded).

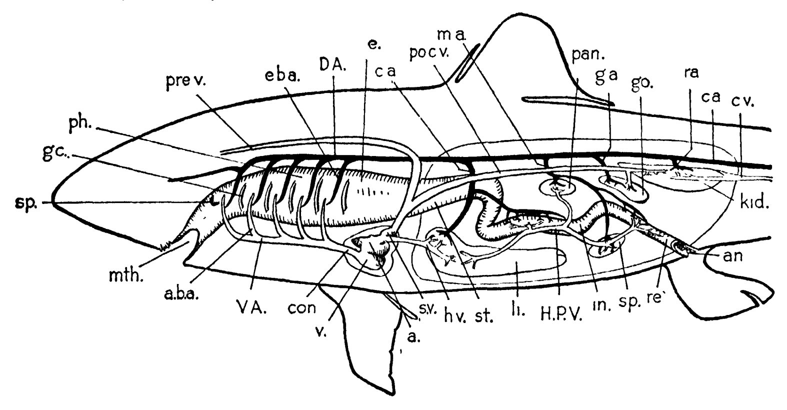


FIG. 210.—Circulation of the dog-fish. sp, spiracle; g.c., gill channel; ph, pharynx; pre. v., precardinal vein; e.b.a., efferent branchial vein; D.A., dorsal corta; e, esophagus; c.a., coeliac artery; po. c.v., postcardinal vein; m.a., mesenteric artery; pan., pancreas; g.a., genital artery; go., gonad; r.a., renal artery; c.a., caudal artery; c.v., caudal vein; kid., kidney; an., anus; re., rectum; sp., spleen; in., intestine; H.P.V., hepatic portal vein, li., liver; st., stomach; h.v., hepatic veins; s.v., sinus venosus; a., auricle; v., ventricle; con., conus arteriosis; V.A., ventral aorta; a.b.a., afferent branchial artery; mth., mouth. (After Mavor.)

The branches of the *dorsal aorta* extend to all other parts of the body, carrying blood: to the kidney, digestive tract, and all structures in head, trunk, and tail (Fig. 210). In all these regions the blood must flow through a second network of capillaries; and as it flows through the various organs, the blood returns to an *unaerated* condition (shaded in Fig. 210). The many veins, which collect unaerated blood from all over the body, all empty into three large veins: the two *precaval* (precardinal) *veins;* which drain the two sides of the head; and the single *postcaval* (postcardinal) *vein,* which drains the viscera, and the body wall of the trunk and tail. These three major veins then

empty, via the *sinus venosus,* into the *auricle* of the heart, thus completing the circuit.

The *single circulation* of the gill-breathing vertebrates—which *collects* and *distributes* oxygen in one and the same circuit—suffices to supply the relatively modest requirements of these cold-blooded creatures. However, the fact that the heart must force the blood against the high resistance of at least two networks of capillaries, before the blood returns to the heart, has tended to limit the efficiency of such a system.

In the higher (lung-breathing) vertebrates, the single circulation has been replaced by a *double circulation.* The birds, Mammals, and many of the reptiles, have developed a respiratory (*pulmonary*) circuit which is entirely separate from the general (*systemic*) circuit of the blood. Such forms possess a *four-chambered* heart. In man, for example, the unaerated blood is collected by the *right* auricle and pumped through the lung capillaries by the *right* ventricle. Then the aerated blood returns from the *pulmonary circuit* to the left auricle and is pumped by the *left ventricle* out into the *systemic circuit.* Thus the four-chambered heart has separate ventricles for pumping blood through the pulmonary and systemic circuits; and such a heart is able to maintain a more rapid circulation. The blood first collects oxygen, in passing through the pulmonary capillaries; and then it returns to the heart for a new impetus, before passing to the capillaries of the systemic circuit, where the oxygen is *distributed.*

The *three-chambered* heart of the Amphibia and the incomplete four-chambered heart of some of the Reptiles represent transitional developments, more or less intermediate between the lower and higher vertebrates. In the amphibian circulation, the single ventricle pumps blood through both the pulmonary and systemic circuits. The unaerated and aerated kinds of blood are received by the right and left auricles respectively, and sent to the ventricle. To a large extent the ventricle keeps the two types of blood separate, sending most of the unaerated through the pulmonary, and most of the aerated through the systemic

circuits. However, there is some mixing; and consequently this kind of system is called an *incomplete double circulation.*

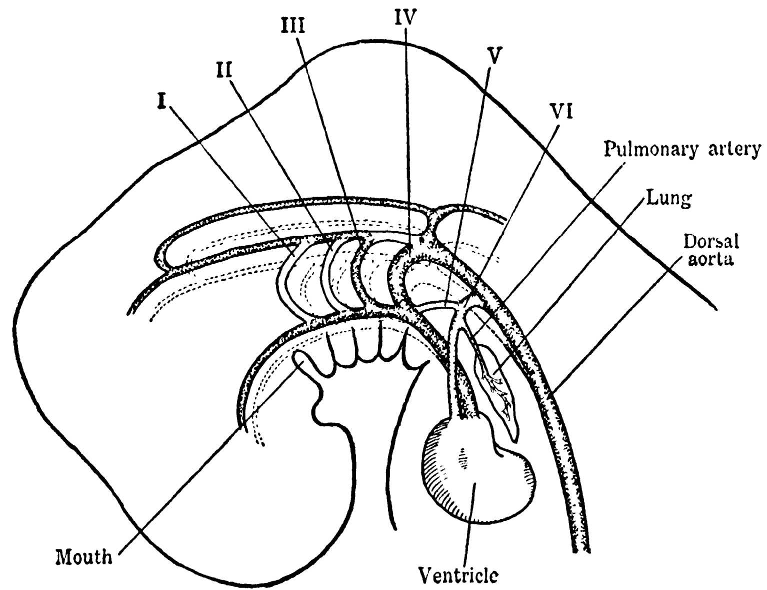
Major Arteries and Veins of the Human Body. In the circulation of man, the main arteries and veins of the systemic circuit, and some of the vessels of the pulmonary circuit are presented in Fig. 206. This figure shows the postcaval and the precaval veins entering the right auricle; and the pulmonary arteries emerging from the right ventricle. However, the figure does not show the pulmonary veins returning to the left auricle, since this chamber lies behind the other structures. The *ventral aorta*, and the *aortic arch*—which loops around the pulmonary artery to reach the *dorsal aorta*—can be seen clearly; as is also true of the lower part of the dorsal aorta. This large artery passes through the diaphragm—near the lower margin of the heart—and continues downward in the abdominal cavity, sending branches to all the lower parts of the body.

The aorta serves as the *trunk line* of the *systemic circulation;* and the major branches of the aorta display essentially the same arrangement in all Mammals. The *innominate* artery (Fig. 206, 4), or first large branch, forks almost immediately into (1) the *right subclavian*, which supplies the right shoulder and arm regions; and (2) the *right common carotid* which supplies the right side of the head as a whole. The second and third large branches of the aorta are, respectively, the *left common carotid* and *left subclavian*. These arteries supply: (1) the left side of the head; (2) the left shoulder and arm.

In the thorax (behind the heart) the aorta gives off a number of small *intercostal arteries* (not shown in Fig. 206), which supply the thoracic body wall. In the abdomen, the aorta sends branches to the digestive tract, kidneys, and abdominal body wall. Finally, the aorta terminates in the lower extremity of the abdominal region, by forking into the *iliac arteries*, which carry blood to the legs.

Development of the Circulatory System. At an early stage of development the embryonic circulation of man and other Mammals is distinctly similar to the circulation of the dogfish and other primitive vertebrates. In the embryo, there

are five pairs of gill clefts, and the six aortic arches branch off from the ventral aorta (Fig. 211). However, this arrangement does not persist as development proceeds. Arches I, II and V are destined to disappear. Arch IV, on the left side, becomes the adult aortic arch; and on the right arch IV becomes the



Redrawn after Patterson, *Embryology*, by permission of Oxford University Press. From Mavor, *General Biology*, by permission of The Macmillan Co.

FIG. 211.—Head of a human embryo, side view, showing the development of the arterial system. I, II, III, IV, V, VI, aortic arches. I, II and V do not persist, while III forms the internal carotid arteries, IV forms a portion of the aorta, and VI forms the pulmonary arteries of the adult.

right subclavian artery. Of the other arteries associated with the human heart, the carotids (Fig. 206) are derived partly from arch III; and the pulmonary arteries come from arch VI (see Fig. 212).

The Hepatic Portal System. The vertebrate circulation displays another distinctive feature which has not been mentioned. Blood from the gastro-intestinal tract does not return directly to the heart, but first passes through the capillaries of the *liver* (Fig. 213). This part of the circulation is called the

hepatic portal system; and the hepatic portal system has an important bearing upon the metabolism of vertebrate animals generally. Blood in the gastro-intestinal capillaries becomes laden with a wide variety of absorbed products. However, many of these compounds never reach the *general* circulation—because the liver intervenes between the intestinal tract and all other parts of the circulation (p. 431).

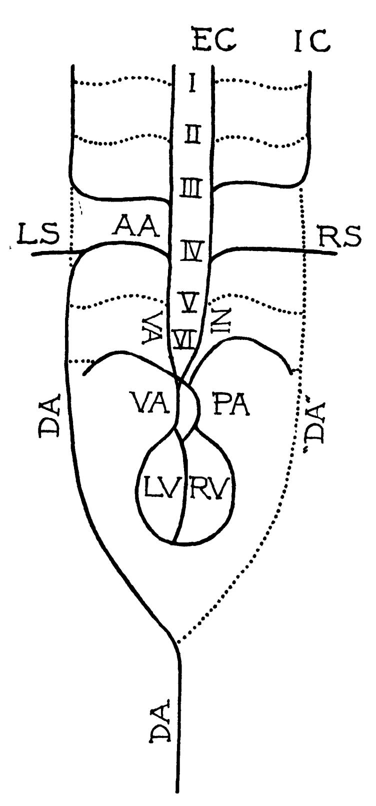


FIG. 212.—Embryonic origin of the major arteries in man and other mammals, I, II, III, IV, V and VI—the six aortic arches of the early embryo. Dotted lines indicate vessels which do not persist in development. LV, left ventricle; RV, right ventricle; VA, ventral aorta; AA, arch of aorta; DA, dorsal aorta; IN, innominate artery; RS, right subclavian; LS, left subclavian; EC, external carotid; IC, internal carotid; PA, pulmonary artery.

The *hepatic portal system* of man is shown in Fig. 213. The *hepatic portal vein* is formed by the confluence of three tributaries: (1) the *gastro-splenic* vein, from the stomach and spleen; (2) the *superior mesenteric vein,* from the upper parts of the small intestine, and (3) the *inferior mesenteric vein,* from the lower small intestine and colon. The portal vein passes directly to the liver and, upon entering the liver, it gives rise to a set of capillaries which extend throughout the liver tissue. Eventually blood drains from the liver by way of the *hepatic veins,* which join the postcava. Accordingly it is important to distinguish clearly between the hepatic *portal* vein, which brings blood *to* the liver, and the *hepatic* veins, which carry blood away from the liver. In vertebrate animals, it is generally not difficult to identify the

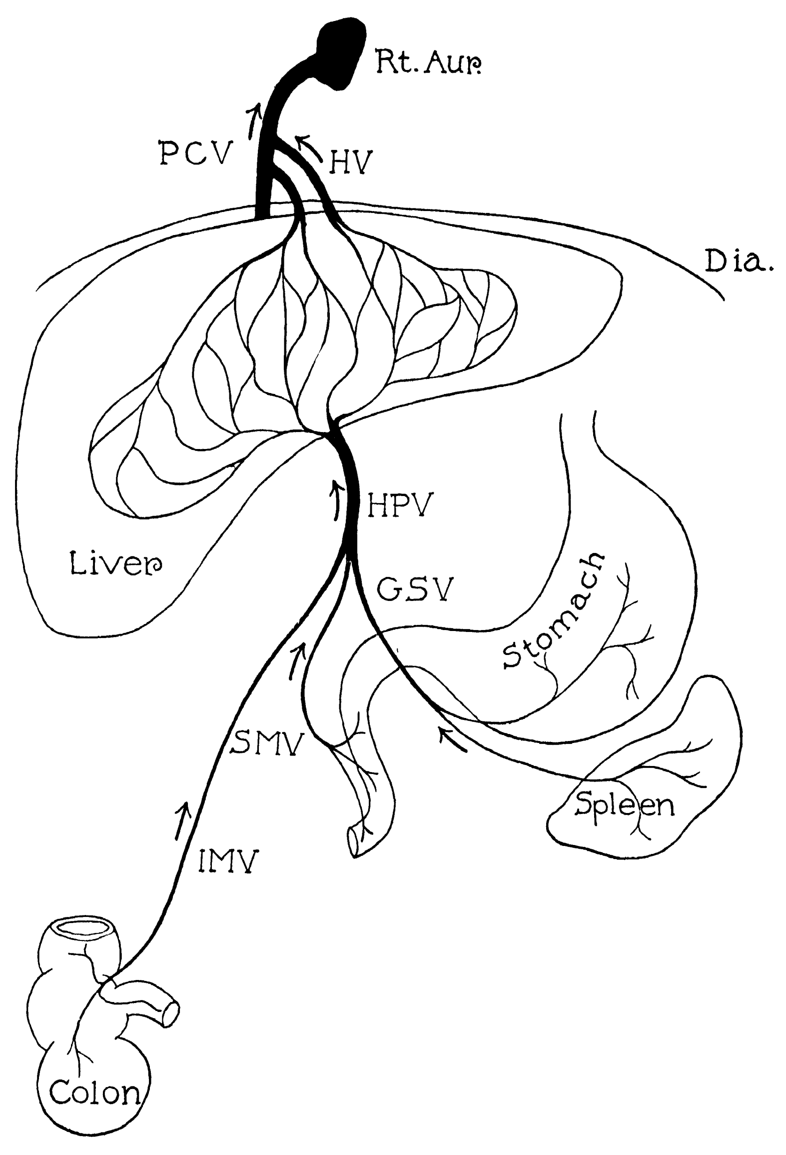


FIG. 213.—The portal circulation of man. HPV, hepatic portal vein, with its tributaries: the gastro-splenic vein (GSV), the superior mesenteric vein (SMV), and the inferior mesenteric vein (IMV); HV, hepatic veins; PCV, postcaval vein; Rt. Aur., right auricle; Dia., diaphragm.

portal vein, because this large vein always originates near the duodenum and runs to the base of the liver, closely accompanied by the *bile duct*.

A portal vein not only originates from capillaries but also terminates in capillaries; whereas other veins originate from capillaries but terminate either by joining some other vein, or by emptying into an auricle. In man and other Mammals, the hepatic portal vein is the only portal vein of the body; but many lower vertebrates also possess a renal portal vein, which brings blood to the kidney (Fig. 210).

The Lymph and Its Origin. Blood in all capillaries continually loses a small proportion of its fluid volume by seepage through the capillary walls. This fluid is the lymph, which filters from the capillaries into the tissue spaces (Fig. 209).

The formation of lymph is not an osmotic process; it is a kind of *forced filtration*, which is energized by blood pressure. Normal blood is slightly hypertonic to the lymph, but the osmotic tendency for water to return to the blood is counterbalanced by blood pressure.

At the arterial end of a capillary, blood pressure is highest—being equivalent, on the average, to a pressure of about 30 mm. of mercury. This pressure exceeds the lymph pressure by about 22 mm.; and since the hypertonicity of the blood is only 15 mm., the effective force which accounts for the formation of new lymph is about 7 mm. of Hg. Near the venous end of the capillaries, where the blood pressure has dissipated somewhat, there is a definite tendency for fluid to re-enter the blood from the lymph. However, the re-entering fluid is of a smaller volume than that which filtered out at the arterial end of the network.

The Composition of Lymph. The lymph is a force-filtrate of the blood and consequently lymph has a composition which is closely related to the composition of the plasma. However, the capillary walls tend to hold back the colloidal components of the blood. Accordingly, lymph contains all the crystalloid components (water, salts, glucose, amino acids, urea, etc.) of the plasma, in amounts which very closely approximate those in the plasma. But the plasma proteins, being colloidal in their

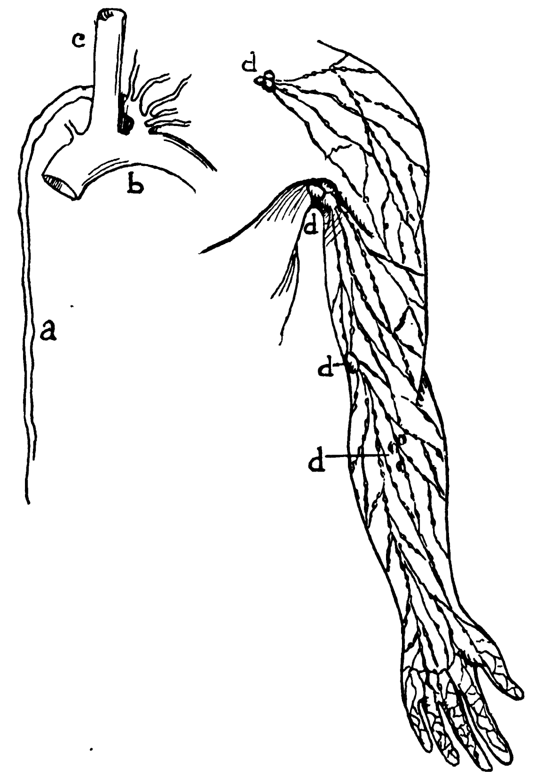
molecular dimensions, are present in the lymph in much lesser amounts than in the plasma. In fact the protein content of lymph is only about ⅓ that of plasma.

The Lymphatic Circulation. In the body it is difficult to find the *lymph vessels,* or *lymphatics,* because they are so delicate. However, the network of lymph vessels (Fig. 214) is very extensive and reaches all parts of the body. The lymphatics drain lymph directly from the tissue spaces, and carry the lymph slowly from the outlying parts toward the thorax.

In the thorax the lymphatic network drains into the two main lymph vessels of the body: (1) the *thoracic duct* and (2) the *right lymphatic duct.* The thoracic duct is the largest lymph vessel in the body, since it drains lymph not only from the digestive tract, but also from the *whole left side* of the body and from the right *leg* and *trunk.* The lymph vessels of the digestive tract pass into the mesentery where they form larger vessels, called the *lacteals.* The lacteals converge toward the root of the mesentery, just below the diaphragm, where they flow together into the *thoracic duct.* This large vessel passes upward through the thorax, where it finally terminates by emptying into the *left subclavian vein* (Fig. 214). Meanwhile the thoracic duct receives tributaries from *all* of the left and *part* of the right sides of the body. The smaller *right lymphatic duct* has an equivalent course and position on the right side of the thorax. It collects lymph from the lymphatic network of the right arm, the right sides of the head, neck, and thorax, and delivers this lymph into the *right subclavian vein.* Thus the lymph, which filters from the blood in all the capillaries of the body, returns to the blood via the subclavian veins.

The Flow of Lymph. Lymph flows very slowly, as compared to blood. A given sample of blood returns to the heart within less than a minute after it is pumped forth from the heart. But an hour or more elapses before a sample of lymph, formed in the leg, finds its way back into the blood stream. Lymph pressure, which sustains this sluggish flow, originates from the fact that new lymph is continually forced from the capillaries into the already filled tissue spaces. Lymph pressure

amounts to only about 8 mm. of Hg; but there are many valves in the lymphatics, and these valves prevent any backflow. Moreover many parts of the lymphatic network lie between the



From Best and Taylor, *The Living Body*

FIG. 214.—On left, thoracic duct showing opening into left subclavian vein (b); a, thoracic duct; c, internal jugular vein. On right, lymphatics of hand and forearm; d, lymph nodes.

muscles of the body—and whenever a muscle contracts and presses against its neighbors, the lymph is driven forward in a considerable part of the local network.

The Lymph Nodes (Glands). These oval masses of *lymphoid tissue* are situated in strategic positions in the lymphatic network, especially at points where the smaller lymph vessels converge to form larger ones (Fig. 214). There are several

groups of unusually large nodes: in the knee and elbow joints; in the groin and armpits; and along the sides of the neck.

The lymph nodes constitute a reserve line of defense against bacterial infection. The lymphoid tissues in the nodes (and in the tonsils, spleen and intestinal wall) give rise to the lymphocytes (p. 401); and the nodes also tend to "strain" the lymph as it passes through. If bacteria from the site of an infection manage to elude the locally mobilized phagocytes, they are carried in the lymph stream toward the more vital centers of the body. But in passing through the lymph glands, most if not all of these bacteria are likely to be destroyed by the phagocytes in the nodes. Accordingly, lymph glands are frequently swollen during any infection; and the position of the swollen glands provides an index of the site of the infection: e.g., a swelling of the nodes of the groin indicates a leg infection; or swellings in the arm-pit indicate an infection in the arm.

Edema. Any part of the body tends to swell if lymph accumulates in the tissue spaces. Such a condition, which is called *edema*, may result from a variety of factors, such as: (1) high blood pressure, as in certain kinds of heart disease; (2) low plasma tonicity due to an excessive loss of plasma proteins, as in chronic kidney disease; (3) abnormally permeable capillaries, due to a severe local damage of the tissues (e.g., spraining an ankle); or (4) obstruction of the lymphatics draining the particular part. In edema, the skin and other tissues become very puffy;.and if pressed, edematous tissue remains indented much longer than is normal.

TEST QUESTIONS

1. Why is a circulatory system essential in all larger animals? What are the general functions of the circulatory system?
2. Specify two kinds of animals possessing direct (hemolymph) circulations, and two kinds of animals possessing indirect (blood-lymph) circulations; explain the essential differences between these types of circulation, and relate these differences to the question of "efficiency."

3. Exchanges between the blood and the cells of an organ cannot occur in the arteries and veins, but only in the capillaries. Is this statement true, and if so, why (at least two reasons)?
4. Differentiate between erythrocytes, leucocytes, and thrombocytes on the basis of:
   a. size and form;
   b. abundance in the blood;
   c. general functions;
   d. origin.
5. Differentiate between diapedesis and phagocytosis; explain the importance of these processes in relation to the body's defenses against bacterial infection.
6. What other defense mechanisms are localized: (a) in the plasma, and (b) in the lymph glands?
7. Without vitamin K the body is unable to synthesize prothrombase.
   Predict the effects of a diet which is very low in K, explaining your answer fully.
8. Propose three different methods by which you might prevent a sample of blood from clotting while you were withdrawing it into a test-tube. Carefully explain the basis of each method in relation to the clotting mechanisms.
9. Differentiate between arteries, veins, and capillaries as to:
   a. structure;
   b. function;
   c. the relative pressure of the conducted blood.
10. Explain the physiological basis for the adage "a man is as young as his arteries," stressing the importance of the "elasticity factor."
11. Make a labelled diagram to show the relations of a capillary to the lymph and the surrounding tissue cells.
12. Assuming that the foregoing tissue is a muscle, explain how and why:
   a. glucose passes from the blood into the cells;
   b. oxygen passes from the blood into the cells;
   c. carbon dioxide passes from the cells into the blood;
   d. other metabolic wastes pass from the cells into the blood.
13. Why is the formation of lymph described as a *force* filtration?
14. Why is this process also called a *colloidal* filtration?
15. Compare the compositions of the plasma and lymph in regard to:
   a. protein content;

b. content of glucose and amino acids;
c. content of urea and inorganic salts;
d. relative tonicity.

16. Carefully explain the balance of forces which accounts for:
    a. the escape of lymph from the plasma;
    b. the back-flow of some lymph into the plasma;
    c. the flow of lymph from the tissue spaces into the lymphatics.
17. Trace the general course followed by the lymphatics which drain the tissue spaces of each of the following regions:
    a. wall of the small intestine;
    b. left side trunk and head;
    c. left leg;
    d. right leg;
    e. right side of trunk and head.
18. Is there any relation between the position of a "swollen gland" (lymph node) and the site of a particular infection? Explain.
19. Explain the relation between muscular activity and the flowing of the lymph. Of what importance are the lymphatic valves?
20. Differentiate between a single and a double type of circulation; and between a two-chambered and a four-chambered heart.
21. On what grounds is the circulation of man and other Mammals regarded as "more efficient" than the circulation of the primitive vertebrates (fish).
22. In man and other Mammals, all the blood which returns from the systemic circuit via the postcaval or precaval veins must pass through the pulmonary circuit before reaching the aorta and starting anew on the systemic circuit (Fig. 206). Demonstrate the truth of this statement by listing in proper sequence the heart chambers, arteries, and veins through which a certain sample of the blood would have to pass in flowing from the postcaval, or one of the precaval veins, to the aorta.
23. List in proper sequence the main branches of the aorta (trunk line of the systemic circuit) and specify the parts or organs supplied by each main branch. What three main veins return the systemic blood to the right auricle?
24. As to the composition (aerated vs. unaerated) of the blood conveyed: (a) how does the pulmonary artery differ from all other arteries; (b) how does the pulmonary vein differ from other veins?

25. Make a labelled diagram to show how the aorta, the carotids, the subclavian and the pulmonary arteries were evolved from the gill arches of primitive vertebrates.
26. Make a labelled diagram showing the relations of the hepatic portal vein to the gastro-intestinal tract, the liver, and the post-caval vein.
27. On the basis of the foregoing diagram, explain why it is impossible for substances absorbed from the gastro-intestinal tract to reach the general circulation without first coming under the influence of the liver tissues.

FURTHER READINGS

1. *The Living Body*, by C. H. Best and N. B. Taylor; New York, 1944.
2. *The Machinery of the Body*, by A. J. Carlson and V. Johnson; Chicago, 1937.
3. *Textbook of Anatomy and Physiology*, by Kimber, Gray and Stackpole; New York, 1935.

CHAPTER 17

ABSORPTION, METABOLISM AND THE DIET

Absorption. The major burden of absorption falls upon the small intestines; and except for water, virtually all organic and inorganic food compounds enter the circulation through the wall of the small intestine.

The large absorbing capacity of the small bowel depends upon its very great surface. The intestinal mucosa comes into contact with the chyme throughout a length of 23 feet; and throughout this distance the intestinal wall is richly supplied with blood capillaries and lymph channels. Consequently ample opportunity is afforded for the blood and lymph in the intestinal wall to come into osmotic equilibrium with the chyme. Moreover, the intestinal mucosa does not have a flat surface. In fact this surface resembles velvet, in that it is studded with numerous hairlike *villi,* which provide at least a tenfold increase of the absorbing area (Fig. 196).

As may be seen in Fig. 215, each *villus* is an absorptive structure, which operates principally on an osmotic basis. A network of blood capillaries extends out into the villus; and there is a *central lymph vessel* at the core. The wall of this lymph vessel, unlike the capillary wall, is perforated by definite gaps, which communicate with the tissue spaces. The blood flows very rapidly through the capillaries of the villus; but the lymph moves very slowly through its channels. Slowly the lymph filters from the capillaries, seeping through the tissue spaces. Then the lymph enters the central lymph vessel and drains away to the network of lymphatics in the wall of the intestine (Fig. 215).

The transfer of food compounds from the chyme into the

blood and lymph is greatly influenced by the structure of the villi. Essentially the chyme is an aqueous solution containing the various digested food products, and these compounds are all able to pass into either the blood or the lymph. But a large part of the *sugars* and *amino acids* are picked up by the blood stream

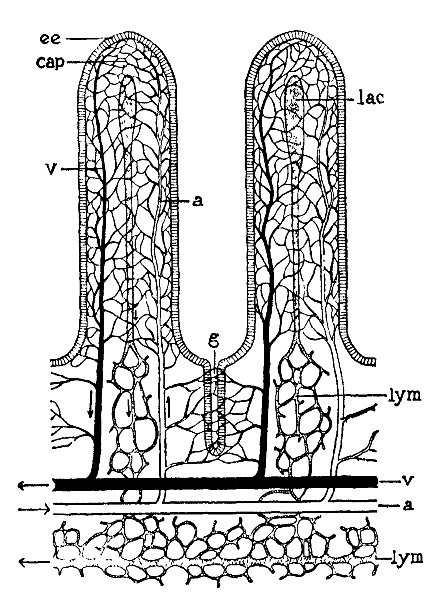


FIG. 215.—Diagrammatic section of two villi, showing the blood vessels and lymphatic vessels. ee, endodermal epithelium; g, gland; a, artery; cap, capillaries; v, vein; lym, lymphatic vessels; lac, the central lymphatic vessel of the villus. Arrows indicate the direction of flow of the blood and the lymph. The interstices among the blood and lymph vessels are occupied by connective tissue, in which the tissue spaces are filled with lymph.

—because the blood keeps changing rapidly in the capillaries. Time is not afforded for the blood to become fully saturated with the food products as they are absorbed. But the lymph flows so slowly that the concentration of each food stuff soon becomes approximately the same in the lymph as in the chyme. Then no more food can enter the lymph, except in very small quantities, as the old lymph is replaced by new.

The absorption of *fatty materials* (glycerol and fatty acids) is quite different. The glycerol and fatty acids recombine into

fats as they pass through the mucosa of the villus; and this resynthesized fat appears in the form of fine globules in the lymph of the tissue spaces—just subjacent to the mucosa. Such fat globules are not able to enter the blood through the capillary walls. Accordingly, the fat globules are slowly carried into the central lymph vessel which conveys them to the lymphatic network. After a fat-rich meal, the *lacteals* (p. 419), passing through the mesentery toward the *thoracic duct*, display a conspicuously white, milky hue, indicating that the lymph at this time is essentially a fatty emulsion.

Water and inorganic salts—like sugars and amino acids—are absorbed primarily into the blood stream. But the quantity of water leaving the small intestine is more or less counterbalanced by the water entering via the digestive juices. The absorption of salts appears to involve forces which modify their osmotic behavior. Certain salts seem to be absorbed preferentially—to an extent that cannot be explained purely in terms of differences in the permeability of the different salts.

In summary, the non-fatty food components are absorbed chiefly into the blood of the hepatic portal system, whereas the fatty foods are taken mostly into the lymph. But since the lymph gradually drains into the blood stream via the thoracic duct, the eventual distribution of all the food components is effected by the blood.

The Liver and Its Special Metabolic Functions. The liver occupies a strategic position in the vertebrate circulation (Fig. 213); and on this account the vertebrate liver has assumed several important metabolic functions. Probably the liver originated as an ordinary digestive gland, but in modern vertebrates it is an exceptionally large mass of tissue, possessing a wide variety of enzymes. All the blood from the digestive tract passes to the liver capillaries via the hepatic portal system. Accordingly, the cells of the liver are in position to extract various absorbed products from the blood and to chemically alter these compounds before sending them on into the general circulation.

Conversion of Other Sugars to Glucose. Although carbohydrates are absorbed into the blood stream mainly in the form

of glucose, small quantities of other monosaccharides (fructose and galactose) also get into the portal circulation. On reaching the liver, these other sugars are converted into glucose—which is the kind of sugar best suited to the needs of the tissues generally.

Regulation of the Blood Glucose Level. During the absorption of a carbohydrate meal, the glucose concentration in the portal blood may rise considerably. But if simultaneously a sample of blood from the general circulation is analyzed, there is not a corresponding rise in the sugar content. The excess sugar has been removed from the portal blood as it flows through the hepatic capillaries. The liver cells convert the extra glucose into glycogen, storing this stable reserve of carbohydrate for the future needs of the body. Thus the liver of a well-nourished dog or man may contain as much as 20 per cent (by dry weight) of glycogen.

Conversely, after fasting, the portal blood contains very little glucose. Nonetheless a sample of blood from the general circulation displays a normal sugar content. The difference has been made up in the liver by a hydrolysis of part of the glycogen reserves into glucose.

The liver, therefore, has the important function of maintaining a constant supply of glucose in the circulation. Normally the blood glucose level remains at about 0.1 per cent; and this amount is just adequate to supply the needs of the tissues. When the glucose absorbed into the portal blood goes higher, the liver stores glucose as glycogen; but when the blood sugar tends to fall below normal, glucose is mobilized from liver glycogen.

This blood-sugar control is of great importance in the economy of the body. *Hyperglycemia,* or excess blood sugar, is wasteful, since the kidneys begin to excrete glucose under this circumstance—and "sugar in the urine" (*glycosuria*) results. Conversely, a gravely lowered blood sugar (*hypoglycemia*) is dangerous. Lacking an adequate sugar supply, the tissues cannot function properly. The patient sinks into a state of *hypoglycemic shock,* which may prove fatal unless glucose is provided quickly—usually by intravenous injection.

Some glycogen is stored in the muscles, and a small amount of this *muscle glycogen* may be drawn upon to maintain the blood sugar. However, muscle glycogen acts mainly as a local fuel deposit, available for muscular work (p. 562).

The endocrine glands (Chap. 21) cooperate with the liver in maintaining the blood sugar level. *Adrenalin* (p. 528) stimulates the liver to convert glycogen to glucose; whereas *insulin* (p. 531) prevents a too rapid breakdown of glycogen. A diabetic patient, lacking insulin, fails to store glycogen in normal fashion; and also the tissues of a diabetic partly lose their capacity to oxidize glucose. In diabetes, consequently, sugar accumulates in the blood and drains off in the urine. The injection of insulin removes both of these impairments—and the blood sugar comes back to normal. Such injections must be calibrated with the utmost care, however. If the injection is too large, the patient may be thrown into "insulin shock" from the resulting hypoglycemia.

After a meal containing large amounts of sugar, a *normal* individual may temporarily display hyperglycemia and glycosuria; but this merely indicates that the liver is not able to cope with such a sudden flood of glucose, absorbed from the digestive tract.

Deamination and Urea Formation. The primary function of the *amino acids* is to enable the tissues to synthesize their essential protein components. An ample protein diet, however, provides the body with an excess of amino acids; and under these circumstances the extra amino acids are used as fuel.

Deamination (p. 163) must occur before an amino acid can be fully oxidized; and in Mammals, this important catabolic function is delegated almost completely to the cells of the liver. During the absorption of a protein-rich meal, a superabundance of amino acids is found in the portal blood. But in the liver, these excess amino acids are *deaminated*. Deamination liberates the CHO parts of the molecules for oxidation by the body tissues; while simultaneously the amino parts of the molecules go into the formation of *urea*, the main nitrogenous waste in man and other *Mammals*.

Deamination, as it is accomplished in the mammalian liver, does not occur by the direct process which was described previously (p. 163). In the liver, in fact, the amino fractions which are discharged from the various amino acids do not appear as free ammonia (NH_3), but are *transferred* to one particular amino acid, namely, *arginine:*

$$\begin{array}{l} C\begin{cases} NH_2 \\ =NH \\ NH \end{cases} \\ \quad\;\; | \\ \quad (CH_2)_3 \\ \quad\;\; | \\ \quad CHNH_2 \\ \quad\;\; | \\ \quad COOH \end{array}$$

arginine

Then arginine decomposes, liberating *urea*. The importance of arginine, therefore, is that it acts as an intermediary in the formation of urea. Arginine receives amino nitrogen from the various other amino acids and transfers this nitrogen to urea, a relatively non-toxic waste product:

$$\begin{array}{l} C\begin{cases} NH_2 \\ =NH \\ NH \end{cases} \\ \quad\;\; | \\ \quad (CH_2)_3 \\ \quad\;\; | \\ \quad CHNH_2 \\ \quad\;\; | \\ \quad COOH \end{array} \xrightarrow[\text{(arginase)}]{+ H_2O} C\begin{cases} NH_2 \\ =O \\ NH_2 \end{cases} + \begin{array}{l} NH_2 \\ \;\;| \\ (CH_2)_3 \\ \;\;| \\ CHNH_2 \\ \;\;| \\ COOH \end{array}$$

arginine urea ornithine

To a small extent the mammalian kidney also engages in the deamination of amino acids. The kidney deaminations are *direct*, however, and lead to production of NH_3 (p. 163). In fact, the kidney utilizes this ammonia in neutralizing various acid metabolites, which otherwise would tend to acidify the urine unduly; e.g.,

$$NH_3 + HOH \rightleftarrows NH_4OH$$

$$NH_4OH + H_2CO_3 \leftrightarrows NH_4HCO_3 + HOH$$

Urea is not eliminated by the liver, but passes through the blood stream to the kidneys. Accordingly, a considerable quantity of this crystalline end-product of amino acid catabolism is present in the urine of man and other Mammals. In birds and reptiles, however, much of the urea is converted, also in the liver, into a more complex nitrogen compound, *uric acid;* and uric acid is the chief nitrogenous waste excreted by these other vertebrates. Some uric acid is also excreted by man and other Mammals; but in Mammals uric acid is derived from the catabolism of nucleoproteins.

The non-nitrogenous compounds produced by the deamination of the amino acids are all relatively simple organic acids (p. 164). These CHO residues may be sent to other tissues in the body; or they may be retained by the liver for conversion into glucose and glycogen. In short, the organic acids liberated by deamination are utilized by the body in one manner or another.

Action of the Liver on Fats. True fats are absorbed mainly in an emulsified form, and cannot pass directly into the cells of most of the tissues. But certain cells, especially in the liver, are able to engulf fat globules—by a process that resembles phagocytosis. In the liver these special cells are called *Kupffer cells.* The Kupffer cells project partially into the capillaries, and in this strategic position they take in fat globules and other granular material from the passing blood stream.

The fats are partially catabolized in the liver before passing to the other body tissues. The liver chemically alters the fatty materials, increasing their capacity to be absorbed and oxidized by other tissues. However, the exact nature of these changes is not clear, although it is known that long-chain fatty acids are partially disrupted by oxidation, and that the partially oxidized end-products are more soluble in the body fluids.

Other Functions of the Liver. The liver has a number of other special functions. Organic toxins (p. 390), produced by

bacteria in the large intestine, are absorbed into the portal blood. But the liver prevents these compounds from reaching toxic levels in the general circulation. A variety of special enzymes are present in the liver cells, and these convert the toxic products into non-toxic compounds. In some cases the toxin is merely combined with some other substance (e.g., benzoic acid is combined with an amino acid, glycine) to form a non-toxic compound, which later is eliminated by the kidneys. However, the *detoxifying* reactions in the liver are very complex and varied.

Other hepatic functions, such as the storage of the *hematinic principal* (p. 400) and the secretion of bile (p. 385) have been mentioned previously; and still other functions, such as the storage of vitamins A and D, will be mentioned later.

General Metabolism: A Balanced Diet. On any long term basis, the daily intake of food must be sufficient (1) to provide the *energy* expended by the body; (2) to provide the *proper kinds of matter* from which the body assembles and synthesizes its essential components. The first of these objectives is fulfilled by catabolism, and the second, by anabolism—each taken as a whole.

The Energy Requirement: Destructive Metabolism. The only source of energy available to the human body is the decomposition of organic compounds, such as proteins, carbohydrates, and fats—and the derivatives of these substances. Carbohydrates and proteins each yield about 4 Calories of energy, and fats provide 9 Calories—per gram utilized in metabolism. Provided the final products of decomposition are the same, these energy quantities are constant—regardless of the intermediary course of metabolism, and regardless of whether the reactions occur inside or outside the living body.

The most direct method of determining the energy expenditure of an individual is to measure the total *heat* output of the body. All other forms of energy (movement, electricity, etc.) which are generated during metabolism, are finally and totally converted to heat, which is given off to the environment.

Measuring the heat output of the human body—a procedure which is called *direct calorimetry*—is very difficult. The subject

must be confined for a long period in a heat-insulated chamber, which is equipped with complicated devices for collecting and measuring the total heat given off by the body. Such experiments have been done, and they prove conclusively that (1) if the caloric content of the utilized foods is just equal to the energy expended, the body weight remains unchanged; (2) if the calories of the food are less than the expended energy, the body weight decreases; and (3) if the energy of the absorbed food is more than that expended, the body weight increases.

In recent times, *metabolism tests* involving a direct measurement of the heat output have been supplanted by *indirect calorimetry*. When this method is employed, the patient's consumption of oxygen and production of carbon dioxide are accurately tallied for a given length of time. These figures provide a basis for calculating not only how much total food has been oxidized, but also the proportions of the carbohydrates, fats and proteins which have been utilized. However, in addition to the oxygen and carbon dioxide data, the output of urea and other nitrogenous end-products must be considered, if an accurate diagnosis of the patient's metabolism is to be obtained.

The Basal Metabolic Rate. The daily energy expenditure varies widely, depending on the general activity of a person, as well as upon a variety of other factors. To obtain the *basal metabolism* it is necessary to standardize conditions very strictly. The subject must fast overnight before the test, and must recline in a completely relaxed condition during the test. Also the *age*, *weight* and *bodily proportions* must be considered in establishing the normal standards.

For a *man* of average proportions (150 pounds, 5 feet, 8 inches), the *normal basal metabolism* is about 1,600 Calories *daily*. More than half of this energy goes toward maintaining the body temperature which is considerably above the usual environmental level. The main loss of heat is from the body *surface*, and consequently the bodily proportions are very important in determining the proper standard. For short stout individuals, the proportion of surface to weight is at a minimum.

Consequently such a person has a normal basal metabolism somewhat lower than 1,600 Calories.

The remainder of the basal energy expenditure represents the work done by the vital organs in the maintenance of life. The heart must work ceaselessly, and this is also true of the muscles of breathing. Under basal conditions not much work is done by the musculature of the digestive tract, or of the body wall, since the subject has been fasting and is not maintaining an upright posture.

In recent years measurements of the basal metabolism are frequently used in medical diagnosis. Abnormally high basal metabolisms are encountered in patients with an overactive *thyroid gland* (hyperthyroidism) and in fevers. A low metabolism, on the other hand, may indicate hypothyroidism; a deficiency of the *adrenal* or *pituitary glands* (p. 533); or just plain undernutrition.

Metabolic Rates Under Other Conditions. If the subject is allowed to eat, but remains in bed, the metabolism rises to 1,800 Calories. The extra energy (200 Calories) goes mainly into the secretory work of the digestive glands, and to the movements of the digestive tract. However, the taking of food, especially proteins, has a stimulating effect upon general metabolism. When sedentary work as well as food is allowed, the metabolism will average about 2,400 Calories. This additional energy (600 Calories) goes mainly to the work of the body muscles, in maintaining posture, and in performing daily routine movements. Under these circumstances, however, the work of the heart is also greater, since a more active circulation through the brain, muscles and digestive tract is required. A manual laborer will usually expend from 3,000-5,000 Calories, depending on the intensity and duration of the work.

Availability of Energy from Different Foods. Disregarding the structural needs of the body and reckoning only in terms of *energy* requirements—one type of food may substitute quite equally for another. A very high protein diet increases the daily output of nitrogenous wastes and puts extra work upon the kidneys; but the kidneys can safely handle the extra load, if they

are in good condition. Too high a proportion of fat (e.g., more than 50 per cent of all the Caloric expenditure) is to be avoided, however. Fatty substances do not "burn" very completely when the tissues lack carbohydrates to oxidize simultaneously.

In the body considerable interconversion takes place among the foodstuffs (p. 159). Many amino acids can be converted to glucose; and carbohydrates can be converted to fat. However, there is only a very limited conversion of fatty materials into carbohydrate, and only the simpler amino acids can be derived from non-protein foods. Most natural foods are mixtures containing some of each kind of the main organic nutrients (Table XV). Consequently the problem of meeting the *energy* requirements of the body is largely a matter of getting a sufficient *quantity* of food.

TABLE XV

ANALYSIS OF SOME COMMON FOODS (PERCENTAGE BY WEIGHT)

	Water	*Protein*	*Fat*	*Carbo-hydrates*	*Inorganic Matter*
Meat	76.6	20.6	1.4	0.2	1.2
Eggs	73.8	12.8	12.2		1.2
Milk	87.8	3.4	3.2	4.8	0.8
White bread	35.7	7.3	0.2	55.6	1.2
Potatoes	75.6	2.2	0.3	20.8	1.1
Fruit	86.0	1.5		10.0	2.5

Starvation. When the total consumption of food is inadequate to meet the energy expenditure, the body begins to sacrifice its existing fund of organic materials. First to go are the carbohydrate stores, mainly the glycogen of the liver and muscles. Simultaneously fat is gradually withdrawn from the adipose tissues. When the fat and carbohydrate reserves have been exhausted, the body begins to consume its own essential structural components—the proteins, phospholipids, etc., in the tissues of the less essential organs of the body. Finally the proto-

plasmic components of the essential organs (brain, spinal cord and heart) are drawn upon; but when this occurs, death rapidly becomes inevitable.

Constructive Metabolism: Essential Kinds of Foods. From an *energy* point-of-view the inorganic foods were not considered, simply because these substances do not supply energy to the body. But there are a number of essential inorganic compounds in the protoplasm; and unless the intake and output of these substances are balanced, the body cannot maintain its normal functions.

Inorganic Requirements. The *water* balance of the body is very important. Each day an average individual loses about 2,000 cc. of water via the urine, sweat, faeces, and expired air. These losses must be restored very regularly, or else the tissues become seriously dehydrated. The body dies of "thirst" more quickly than from starvation in the ordinary sense.

The replenishment of salts is also important. The body loses about 30 grams of assorted minerals each day—via the urine, sweat, and faeces. Most natural foods contain approximately the proper proportions of the protoplasmic salts (p. 91), although plant foods are generally low in NaCl. Consequently man has learned to use the crystalline form of this salt, to supplement his own diet—and the diets of his domestic animals.

Severe muscular work carried on in a hot environment induces a very large loss of salts (and water) via the perspiration. When this condition is carried to an extreme, the worker develops "miner's cramp," a painful spasm involving a large part of the muscular system. Such workers are rabidly thirsty, but to drink water only aggravates the condition—by increasing the flow of sweat and accelerating the loss of salt. Finally it was learned that salt water should be provided, and during hot heavy work, salt solutions can be drunk without distaste.

Certain *specific* minerals are regularly needed by the body for the synthesis of its essential components. The minerals most likely to be deficient in the diet are iron, calcium and iodine. Without a source of iron, from the organic and inorganic components of our food, the body cannot continue to synthesize

hemoglobin, and anemia must result. However, most meats (especially liver), eggs, and many fruits and vegetables, provide an adequate source of iron. Calcium compounds are necessary for the formation of bone and teeth: about 1.0 gm. for children; 2.0 gms. for women during pregnancy and nursing; and 0.8 gm. for other adults—computed on a daily basis, in terms of the calcium content. The best source of this mineral is milk, although cereals, and such vegetables as beans and peas, are also rich in calcium. Most meats provide a good source of phosphorus, which is also essential for the teeth and bones.

Without iodine the body cannot synthesize *thyroxin*, the essential hormone of the thyroid gland; and the resulting *hypothyroidism* (p. 526) represents a very serious and, in former times, fairly prevalent disease. Iodine is especially abundant in the sea and in sea-foods. Formerly, iodine deficiencies were encountered mainly in populations living in inland regions which never were inundated by the ocean during any geological period. Nowadays, however, dietary hypothyroidism (including *cretinism*) is seldom found—due mainly to the fact that commercial salts are artificially fortified by the addition of small amounts of potassium iodide (KI).

Recent investigations indicate that health-maintaining diets must contain zinc, copper, manganese, cobalt, and perhaps one or two other metals. But only the merest traces of these substances are sufficient. These *trace metals* appear to be needed for the formation of some of the metabolic enzymes; and most natural diets contain more than adequate amounts of the trace elements.

Organic Requirements. In addition to the fuel foods, at least 50 gms. of protein must be included in the diet of an adult; and more protein is needed in growing individuals. Such a quantity of protein provides only the minimal amount and variety of the amino acids needed by the tissues for the synthesis of structural proteins. As in animals generally, the cells of the human body can synthesize only a few of the amino acids from simpler substances. Consequently the body depends upon a ready-made supply of all the non-synthesizable amino acids.

Not all protein foods are equally valuable in contributing these *essential amino acids*, as may be seen in Table XVI.

TABLE XVI *

CHARACTER OF PROTEINS IN SOME COMMON FOODS

Food	*Chief Proteins Present*	*Amino-acid Constitution*
Milk and cheese.	Casein Lactalbumin	Complete, but low in cystine Complete
Corn (maize)	Zein	Lacks lysine and tryptophane, and is low in cystine
Eggs	Ovalbumin Ovovitelline	Complete Complete
Meat	Albumin Myosin	Complete Complete
Peas.	Legumin Gliadin	Incomplete, low in cystine Incomplete, lacks lysine
Wheat	Glutenin	Complete
Gelatin	Gelatin	Incomplete, lacking tryptophane and tyrosine; very low in cystine

* From Best and Taylor, *The Living Body.*

Some natural fat must also be included in a balanced diet. The body is able to synthesize all except a few of the fatty acids, but these specific exceptions are completely essential. Also fats are our only natural source of some of the vitamins—without which the body cannot grow or function.

The Vitamins. In 1912 it was definitely proved that *animals* cannot survive on diets in which the organic food is provided entirely by purified proteins, carbohydrates and lipids. This result indicated that the natural sources of organic food must contain small amounts of unknown essential substances which were named the vitamins. Since 1912, many experiments have been

performed, using all kinds of controlled diets; and these experiments have amply substantiated the *vitamin hypothesis.* At the present time, therefore, it is possible to define the missing factors very precisely. The vitamins are a group of simple specific organic compounds which animals must include in their regular diet in order to maintain normal growth and health. If any of the vitamins necessary to the species is regularly absent from the diet, the animal begins to show specific symptoms, which can be recognized as one or another of the *deficiency diseases,* or avitaminoses; and eventually the animal dies unless the deficiency is corrected.

Because of its historic interest, vitamin C will be used to exemplify the vitamins generally. Scurvy, the *avitiminosis* which develops when vitamin C is absent from the diet, was described very accurately by Richard Hawkins, more than 350 years ago. Hawkins, a captain in the English navy, observed the bleeding gums, bruised skin, anemia, and general weakness which developed in the crew when a sailing vessel had been at sea for many months—after all supplies of fresh fruits and vegetables had been exhausted. Also Hawkins observed that a small amount of lime juice, added to the daily menu of the crew, was completely effective in preventing the development of the *scorbutic symptoms.*

In 1933, vitamin C was isolated in pure form; and it proved to be ascorbic acid ($C_6H_8O_6$). Meanwhile, many other vitamins have now been identified (Table XVII), and all have proved to be relatively simple organic compounds which can be absorbed without digestion—if they are present in the foods of the animal. Moreover, each vitamin is specific in relieving the particular symptoms caused by its deficiency. Only ascorbic acid (or compounds from which the body can derive ascorbic acid) is effective in preventing or relieving the specific symptoms of scurvy (Fig. 216).

The minimum daily requirement of each vitamin is very small. Ten milligrams (.01 gm.) of ascorbic acid, and considerably less of most of the other vitamins, is entirely adequate

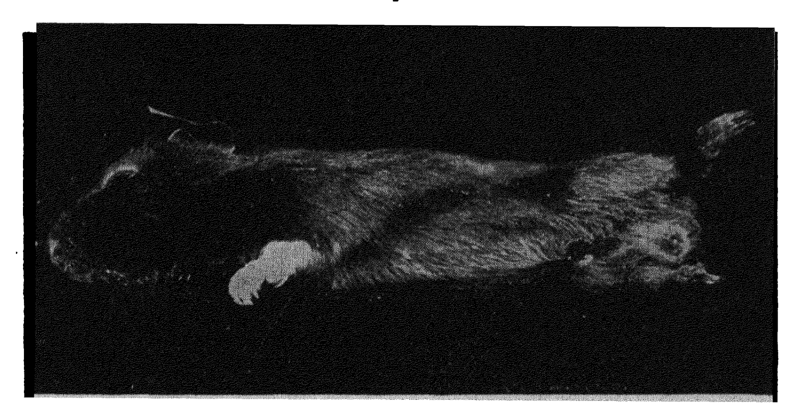
Table XVII

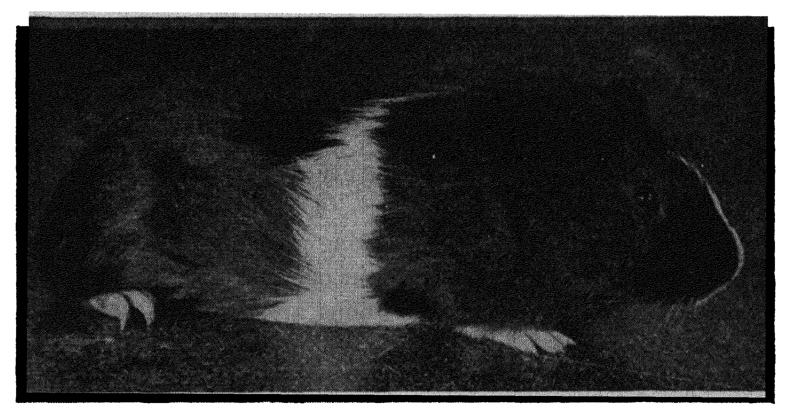
PRINCIPAL VITAMINS

Names and Chemical Constitution	*Deficiency Effects*	*Good Natural (Food) Sources*
Vitamin A, $C_{20}H_{30}O$; provitamin = carotene, $C_{40}H_{56}$, a yellow plant pigment	Night blindness, in mild cases; xerophthalmia, in severe deficiency; abnormal changes in various epithelial membranes; retarded growth	Animal oils, especially the liver oils of certain fish; egg yolk; yellow and green vegetables
Vitamin B_1; thiamin, $C_{12}H_{16}N_4SO$	Beri beri, polyneuritis: loss of appetite, weight and vigor; progressive paralysis, retarded growth	Cereal grains, especially the outer seed coats; meats, especially pork; yeast
Vitamin B_2; riboflavin, $C_{17}H_{20}N_4O_6$	Predisposition to cataract; defective skin patches around mouth and ears; deranged metabolism and retarded growth	Associated with B_1 and other members of the B-complex
Vitamin P-P; niacin, $C_6H_5NO_2$, pellagra-preventing vitamin	Uncomplicated pellagra; retarded growth	Part of the B-complex
Vitamin C; ascorbic acid, $C_6H_8O_6$	Scurvy, retarded growth	Juices of the citrus fruits (lemons, limes, oranges, etc.); many vegetables
Vitamin D; calciferol, $C_{28}H_{44}O$, formed by U-V radiation from ergosterol	Rickets; faulty bones and teeth; deranged calcium metabolism; retarded growth	Animal oils, such as butter, milk and the liver oils of fish
Vitamin E; α-tocopherol, $C_{29}H_{50}O_2$	Sterility in rats, but probably not in man; females fail to retain embryos; males fail to form functional sperm	Vegetable and animal oils; wheat germ oil, particularly
Vitamin K; $C_{31}H_{46}O_2$	Improper coagulation of blood; insufficient synthesis of prothrombase; improper growth	Leafy vegetables; alfalfa

in preventing a deficiency. Consequently it is plain that the vitamins are not important as sources of energy for the body. Rather the vitamins represent important structural components in the protoplasm. However, aside from our knowledge that certain

vitamins (B_1, B_2 and the P-P factor) provide the *prosthetic substances* of several important oxidizing enzymes in the tissues—little is known about the precise functions of the vitamins.





Courtesy of E. R. Squibb & Sons, New York

FIG. 216.—Upper photo: Drastic scurvy in a guinea pig. Lower photo: Restoration with pure ascorbic acid (crystalline vitamin C).

Facts About Some Other Vitamins. Vitamin research has advanced very rapidly in the past ten years, and only a brief description of the firmly established results can be presented in this account.

Vitamin A is a colorless compound ($C_{20}H_{30}O$); but the body can derive vitamin A from *carotene* ($C_{40}H_{56}$)—an orange pigment present in many green and yellow vegetables. A drastic

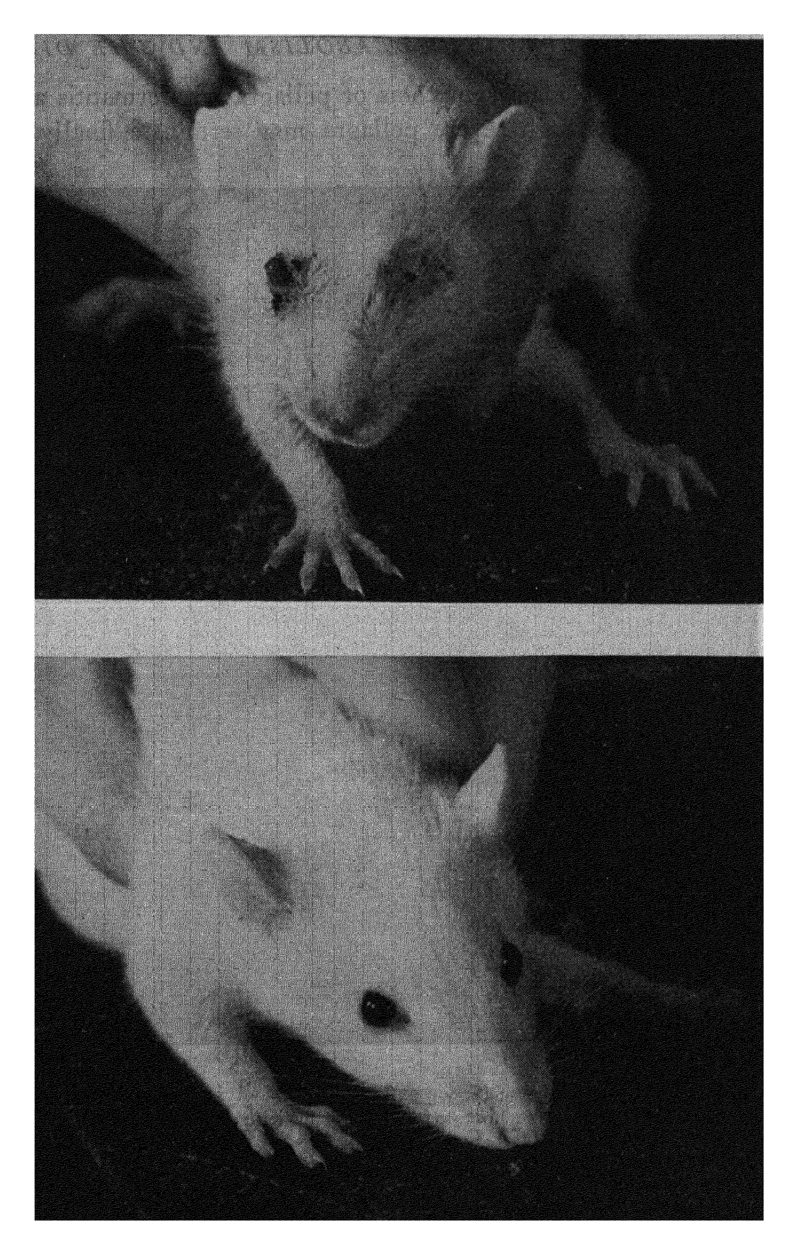
deficiency of vitamin A leads to a serious eye defect, called xerophthalmia, in which the cornea becomes very dry and ulcerated (Fig. 217). Recently it has been shown that vitamin A plays an important role in vision. In fact the retina uses vitamin A in synthesizing *visual purple*—one of the photosensitive pigments of the eye. Vitamin A is one of the group of the *fat-soluble* vitamins (A, D and E), which are stored to some extent in the liver; and this accounts for the fact that liver oils, derived from fish such as the cod, halibut, and shark, are excellent natural sources of these vitamins.

Previously the *B-complex* of vitamins was thought to be a single compound. Now, however, *at least* seven separate B vitamins have been identified, although only four of these will be discussed.

A deficiency of *thiamin*, or vitamin B_1, gives rise to *polyneuritis*, or *beri beri*—as it is usually called in man. Drastic polyneuritis involves degenerative changes in the peripheral nerves (p. 582), which lead to a severe progressive paralysis. This paralysis disappears very rapidly, however, when thiamin is given: e.g., a polyneuritic laboratory animal frequently regains normal muscular movement in one hour, after the vitamin is injected intravenously (Fig. 218). Drastic beri beri became prevalent for a time among rice-eating populations—when modern methods of polishing the grain began to be adopted. The outer seed coats of the cereal grains are excellent sources of thiamin and the other vitamins of the B-complex—and consequently highly refined grain is a poor substitute for whole grain.

A deficiency of vitamin B_2 (*riboflavin*) leads to various symptoms, including: (1) loss of weight; (2) a scaliness of the skin around the mouth and ears; and (3) a predisposition to cataract (Fig. 219). Riboflavin, like thiamin, forms the prosthetic group of at least one of the oxidative enzymes present in many tissues.

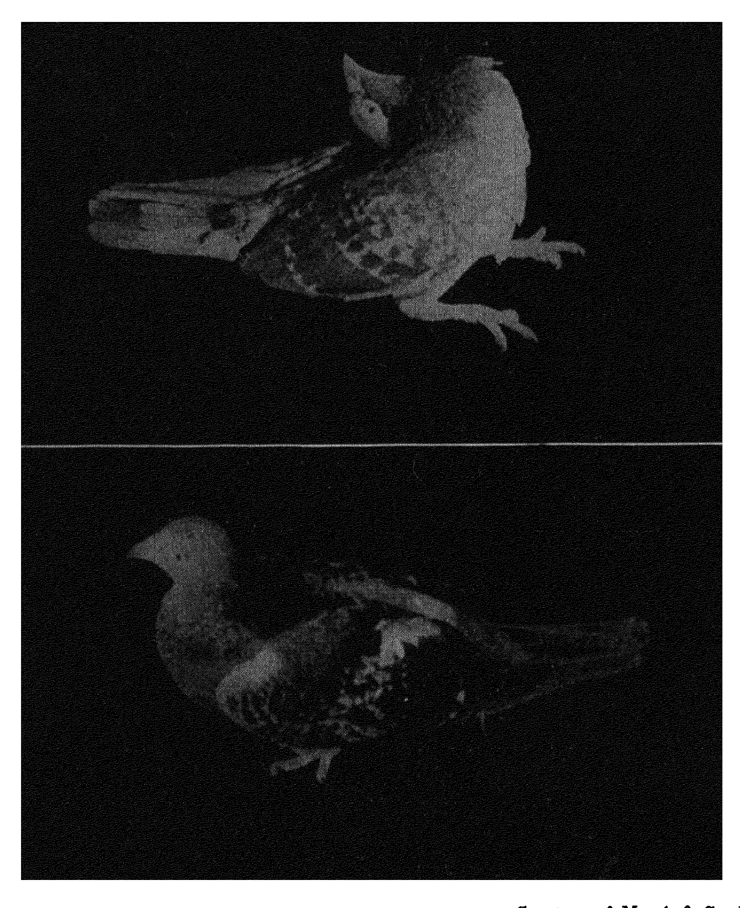
Pellagra is still a fairly prevalent deficiency disease. This is especially true in some districts of the South Atlantic States, where the traditional diet is restricted mainly to maize, molasses



Courtesy of E. R. Squibb & Sons, New York

FIG. 217.—Upper photo: Drastic vitamin A deficiency, showing blindness, due to an ulceration of the cornea. Lower photo: Restoration of the eyes after feeding adequate quantities of vitamin A.

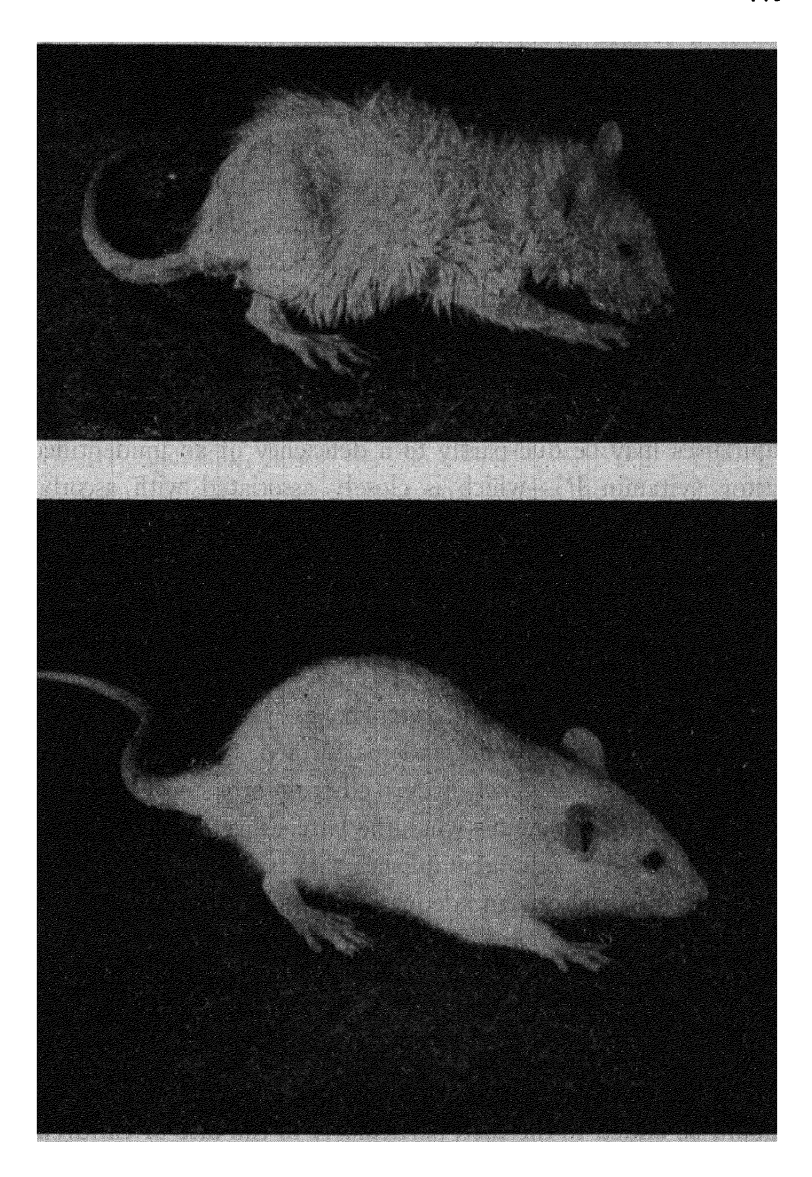
and meat. The main symptoms of pellagra are dermatitis and diarrhoea, although severe pellagra may terminate finally in



Courtesy of Merck & Co. Inc.

FIG. 218.—Upper photo: Pigeon suffering from polyneuritis. Lower photo: Same bird less than three hours after treatment with thiamin (vitamin B_1).

prostration and death. The main pellagra-preventing (P-P) factor is *niacin*, which also has been called nicotinic acid, although many cases of pellagra are complicated by an absence of other B-complex vitamins. Niacin has become available—since the vitamin has been isolated and synthesized artificially—but



Courtesy of E. R. Squibb & Sons, New York

FIG. 219.—Upper photo: Deficiency of riboflavin retards growth and induces certain changes in the skin. Lower photo: Same animal, restored to normal by riboflavin feeding.

traditions of diets are hard to eradicate, and pellagra still remains a serious problem. Vitamin B_6 (*pyridoxin*)—the anti-dermatitis factor—is frequently absent from the pellagra diet, and this vitamin may be responsible for the skin complications which are almost always observed in clinical pellagra.

In scurvy, the main symptoms are generally attributed to a weakening of the walls of the arterioles and capillaries. The scorbutic animal displays spontaneous bleeding—in the gums and joints, and beneath the skin—and this may account for the fact that scorbutic individuals are very susceptible to bruises. Probably the anemia is likewise a result of internal bleeding; although some recent work indicates that the fragility of the capillaries may be due partly to a deficiency of an unidentified factor (vitamin P)—which is closely associated with ascorbic acid in many foods.

Rickets—which is caused by a deficiency of vitamin D—was fairly prevalent about twenty-five years ago, although the spindly crooked legs of the rachitic child are seldom seen in recent years. In rickets, the deposition of calcium and phosphorus compounds in the growing bones is faulty; and consequently the bones are weak and malformed.

Vitamin D, or *calciferol*, is derived from ergosterol, a closely related steroid compound—when the latter is irradiated by ultraviolet light. The body accomplishes this transformation in the skin, provided there is an adequate exposure to direct sunlight, or to some other source of ultraviolet radiation. Ergosterol, which is called the pro-vitamin, is present in many animal fats such as butter; and in summer vitamin D deficiencies are relatively rare. But in winter—and under other conditions of reduced sunlight—supplementary concentrates of vitamin D should be added to the diet, particularly in the case of children, and of women during pregnancy and lactation.

Vitamins E and K have been identified only quite recently. A deficiency of vitamin E (α-tocopherol) induces sterility, at least in some animals, such as the rat. Female rats abort their young long before the normal time of birth; and males become sterile, due to degenerative changes in the testes. However,

such changes have not been demonstrated in man, despite a number of experiments. Vitamin E is widely found in animal and vegetable oils, and perhaps an E-deficiency never occurs under ordinary dietary conditions.

With a deficiency of vitamin K, the body does not synthesize adequate quantities of *prothrombase;* and consequently the coagulating capacity of the blood becomes impaired. In maternity hospitals vitamin K is now regularly administered just before child-birth, with a significant reduction in mortality from hemorrhage in the new-born children, as well as in the mothers.

Origin of the Vitamins. Plants synthesize the vitamins, and probably plants need these compounds just as much as animals. Strictly speaking, however, the vitamins are food compounds, and since plants require no organic foods, the term vitamin is scarcely applicable in holophytic organisms. Some animals also have a capacity for synthesizing certain vitamins. Rats, for example, can synthesize ascorbic acid, and consequently scurvy never develops in this species. Man likewise can subsist on diets containing little or no thiamin—but in this case the vitamin is formed by the bacteria which inhabit man's large intestine.

Summary. Only a carefully balanced diet will sustain growth and health in man and other animals. The daily energy expenditure must be balanced by an adequate caloric content in the food; and the food must provide adequate amounts of all substances needed in constructive metabolism. These structural requirements include: water, various essential inorganic salts, a minimum of proteins and natural fats, and a full assortment of such vitamins as are essential in the particular species.

TEST QUESTIONS

1. Specify three factors which account for the fact that a large proportion of our organic food is *absorbed* from the small intestine.
2. Make a labelled diagram of one of the intestinal villi, showing its relations to the blood vessels and lymphatics of the intestinal wall.

3. What factors help to explain the fact that fatty components of our foods are absorbed mainly into the lymph stream rather than into the blood stream?
4. What factors account for the fact that the end products of the digestion of our non-fatty foods are absorbed mainly into the blood stream rather than into the lymph stream?
5. Specify at least five metabolic functions performed by the liver. How can you account for the fact that the vertebrate liver has assumed so many important functions?
6. Under what circumstances would you expect to find:
   a. galactose and benzoic acid in all parts of the blood stream;
   b. that blood entering the liver (portal blood) contains more glucose than blood leaving the liver (hepatic blood);
   c. that the hepatic blood contains more glucose than the portal blood?
7. How are (b) and (c) of the previous question related to glycogen storage and the maintenance of a steady blood-sugar level?
8. What are the symptoms of hypoglycemia and hyperglycemia, and how are these conditions related to insulin and adrenalin?
9. When the diet is very low in protein foods, scarcely any of the absorbed amino acids are deaminated in the body and very little urea appears in the urine. Explain fully.
10. A high protein diet is accompanied by a large urea production. Explain.
11. In man's liver and kidney the deamination reactions are quite different. Explain fully.
12. Explain why the total energy expenditures of the body are measured in terms of Calories (i.e., heat units).
13. What is meant by the basal metabolism of an individual; how is the B.M. usually measured; and why is this basic energy expenditure essential for the maintenance of life?
14. Assuming that the energy deficit is made up partly (⅔) by sacrificing the glycogen reserves and partly (⅓) by oxidizing reserve fat, how much weight will a man lose in one week if his daily food provides only 2,000 Calories while his daily work demands an expenditure of 2,500 Calories?
15. During starvation, the organic components of the body are sacrificed in a way that a maximum time of survival is assured. Explain fully.

16. The daily diets of four college students are given below. Appraise each diet and explain the consequences of the deficiencies (if any):

    Diet A:
    - Water, salts, and vitamins, adequate
    - Fats, 100 grams
    - Starch, 100 grams
    - Protein, 50 grams.

    Diet B:
    - Water, adequate
    - Salts, adequate quantity but lacking in iodides
    - Vitamins, adequate
    - Carbohydrates, 500 grams
    - Fats, 50 grams
    - Proteins, 25 grams.

    Diet C:
    - Water, salts, and vitamins, adequate
    - Proteins, 600 grams
    - Fats, 50 grams
    - Carbohydrates, virtually none.

    Diet D:
    - Water, salts, and vitamins, adequate
    - Carbohydrates, 400 grams
    - Fats, 50 grams
    - Proteins (all from corn and gelatin), 200 grams.

17. Select any one of the known vitamins and explain how and why it is typical of the vitamins generally.
18. The physiological roles of some of the vitamins are now partially understood. Explain the statement carefully, citing at least two specific examples.
19. A doctor's new patient is observed to have bow legs, poor teeth and he stumbles over a foot-stool in the dimly lighted office. Prescribe: (a) the proper purified vitamins (if the patient can afford this), or (b) a fortification of the diet by appropriate foods.
20. Prescribe, as above, in the following cases:
    a. the patient complains of a lack of "pep" and appetite and a thorough examination fails to reveal any tangible pathology;

b. the youngster is "small for his age," has scaly patches around the mouth and ears, and doesn't see very well.

FURTHER READINGS

1. *Chemistry of Food and Nutrition*, by H. C. Sherman; New York, 1937.
2. *Vitamins*, by Henry Borsook; New York, 1941.

CHAPTER 18

RESPIRATION

WITHOUT oxygen the cells of the body deteriorate quite rapidly. First to go are certain parts of the brain which may be damaged irreparably by less than five minutes of *complete* asphyxiation. This probably represents an extreme of vulnerability—but the fact remains that the cells of most animals need a fairly constant supply of oxygen. Also, the carbon dioxide produced by the body must constantly be removed, if the cells are to maintain their living structure and activity.

The problem of respiration is not very acute among small aquatic animals, like Paramecium or Hydra. The respiratory gases have a relatively high diffusion rate. Oxygen from the surrounding water enters the protoplasm of such small organisms as fast as it is consumed; and carbon dioxide passes out to the environment before it accumulates unduly in the protoplasm. Therefore no specialized respiratory structures are necessary among such small aquatic forms.

With larger animals, the deeper lying tissues would soon be asphyxiated if they depended solely upon diffusion in obtaining their oxygen and disposing of their carbon dioxide. Oxygen from the environment would be used up by the superficial cells before it could reach the deeper ones; and the superficial tissues would be called upon to eliminate not only their own carbon dioxide, but also that produced by the deeper cells. Accordingly the problem of respiration becomes more acute as the mass of the animal body becomes greater; and in all larger animals the *circulatory system* takes over the function of transporting the respiratory gases between the deep-lying tissues and the *respiratory surface.*

With the intervention of the circulatory system, the processes of respiration become more complicated. In fact, the respiration of higher animals involves three processes: i.e., (1) *external respiration*—the exchange of oxygen and carbon dioxide between the blood and the environment; (2) the *transportation* of oxygen and carbon dioxide in the blood stream to and from the various tissues; and (3) *internal respiration*—the exchange of

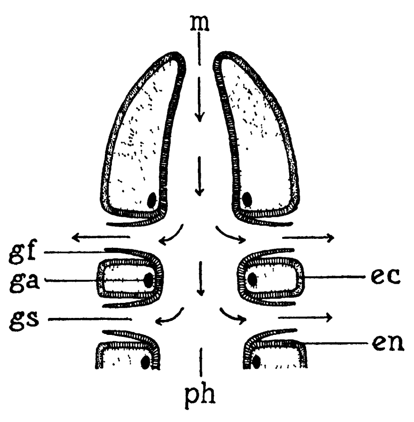


FIG. 220.—Diagram of the gills of a fish (shark). Arrows indicate the direction of flow of water. m, mouth; ph, pharynx; gs, gill slit; ga, gill arch; gf, gill filament; ec, ectoderm; en, endoderm.

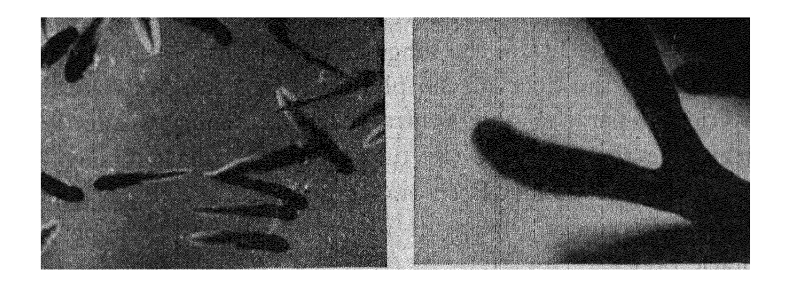
oxygen and carbon dioxide between the blood and the tissues of the body.

External Respiration. Each animal is equipped with some sort of moist surface at which the blood undergoes *aeration*. Typically the *respiratory surface* comes into direct contact with the environing air or water; and the respiratory surface is provided with an extensive network of capillaries immediately beneath the surface. At such an osmotic surface, equilibrium occurs very quickly between the blood and the environment: i.e., oxygen quickly enters and saturates the blood; and carbon dioxide leaves the blood, entering the environment.

In animals like the earthworm, the entire body surface takes part in external respiration; but this is not a very efficient arrangement. To facilitate a rapid aeration of the blood, the re-

spiratory surface must be moist and delicate, and this makes it susceptible to external injury. The earthworm, for example, cannot leave the protection of its burrow, except for relatively short periods. Exposure to sunlight shrivels and hardens the delicate skin of the earthworm—and when this occurs, respiration goes on so slowly that the animal dies of asphyxia.

Gills. Most *aquatic animals* have developed *gills* (Fig. 220) which serve as specialized organs of external respiration. Typical fish, for example, possess a hard scaly surface covering most of the body. Such a surface protects the individual from injurious contacts; but it is not a suitable surface for aeration. But the delicate *gills* of the fish provide an excellent surface for the aeration of the blood. The gills lie in a protected position in the *gill clefts*, which lead from the pharynx to the exterior of the body. The fish takes in a continuous stream of water, which passes through the mouth and out through the gill clefts—bathing the soft fleshy gills. Typically each gill is a highly lobulated mass, which is well supplied with blood capillaries (Fig. 221). This arrangement provides an adequate osmotic surface across which oxygen and carbon dioxide are exchanged between the blood passing *through* the gill and the water passing *over* the gill.



A B

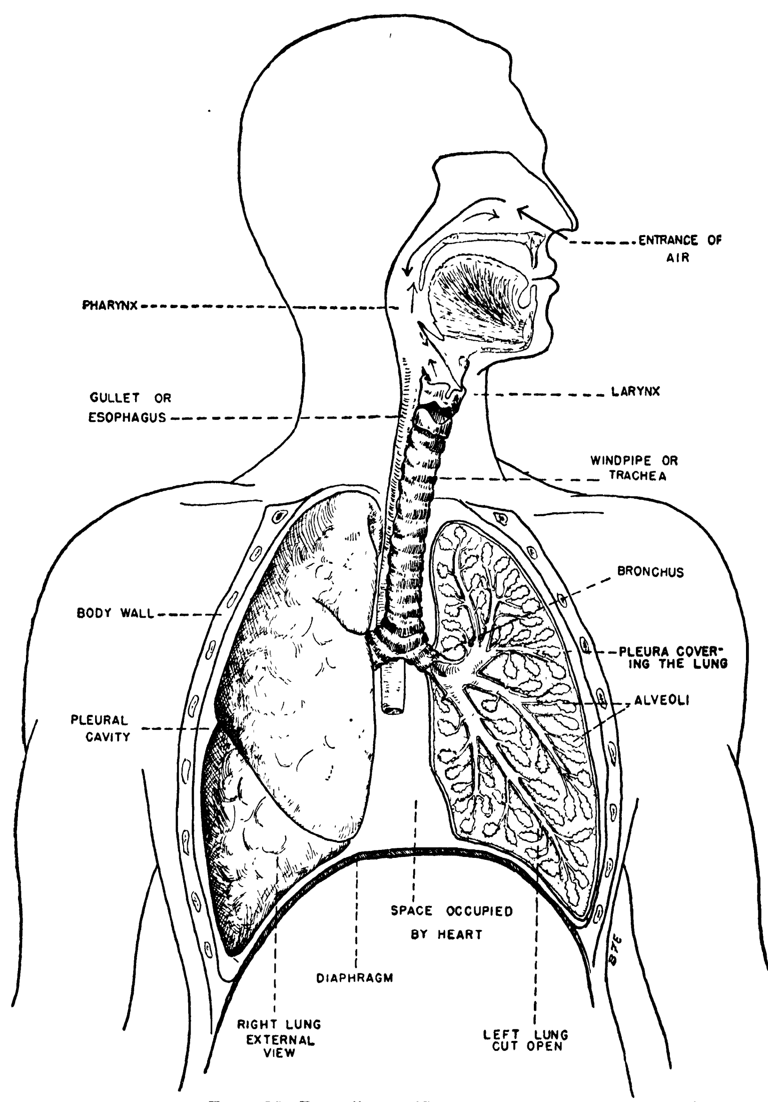
FIG. 221.—A. The gills of the tadpole are fleshy outgrowths which protrude from the sides of the body, just behind the head. B. Part of one gill, highly magnified. The capillaries in the gill form a network of dark channels.

Lungs. Gills are not well suited to terrestrial conditions because they are too exposed and vulnerable to the drying effects of the atmosphere. Instead of gills, most land animals have developed *lungs*. Essentially a lung is a deeply inpocketed respiratory surface, which is not exposed directly to the external atmosphere. Accordingly lung-breathing animals have developed ways and means of ventilating the recesses of the lungs. Unless air in the lung sac is changed from moment to moment, oxygen is soon depleted from the pulmonary air, and carbon dioxide accumulates to toxic levels.

In higher vertebrates the lungs arise as a simple tubular outgrowth from the floor of the pharynx. This *lung bud* pushes posteriorly—parallel and ventral to the esophagus—until it reaches the thorax. Here the tube forks, sending a branch to each side of the thorax. Each branch gives rise to a lung, which eventually occupies almost all the corresponding side of the thoracic cavity.

The unbranched portion of the air passage (Fig. 222) becomes the *larynx* and *trachea;* and the two main forks become the *bronchi.* On entering the lung each bronchus gives rise to many branches, which form the smaller *bronchioles* in all parts of the lung. Eventually each bronchiole terminates blindly—by leading into a cluster of tiny air chambers, the *alveoli* (Fig. 223). Each alveolus lies in intimate contact with a network of capillaries and, in the human lung, there is an alveolar surface of more than 1,000 square feet across which an aeration of the blood occurs. All the many branches of the "bronchial tree" are held in place by elastic connective tissue which fills in the interalveolar spaces; and each lung is covered as a whole by its own external epithelium.

If removed from the body, the lung shrinks down into a relatively small spongy mass. Such a deflated lung may be reinflated through the trachea—in which case the walls become stretched like those of a toy balloon. But if the inflation pressure is released, the elasticity of the stretched pulmonary walls again deflates the lung, expelling most of its content of air.



From MacDougall and Hegner, *Biology,* McGraw-Hill Book Co.

FIG. 222.—The human respiratory system. (B. F. Edwards.)

The free transit of air to and from the lungs is assured by the fact that the walls of the larynx, trachea, bronchi, and larger bronchioles are reinforced with cartilage—which prevents the passages from collapsing (Fig. 222). In the trachea and bronchi the cartilaginous reinforcements take the form of a series of ringlike bands. But the larynx, which houses the *vocal cords*, is strengthened by a larger single encasement of cartilage (Fig. 222).

Each lung is covered externally by a smooth epithelium, which is called the *pleura;* and also there is a pleural lining on the inner surface of the thorax wall (Fig. 222). Thus between the two layers of the pleura there exists, at least potentially, a cavity which is called the *pleural cavity*. Normally the pleural cavity is practically obliterated by the fact that the outer surface of the lung lies in intimate contact with the inner surface of the thoracic wall. However, if the pleural linings become inflamed, as in pleurisy, fluid tends to accumulate in the pleural cavity.

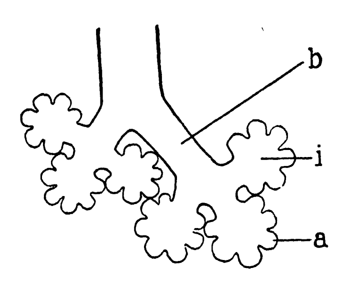
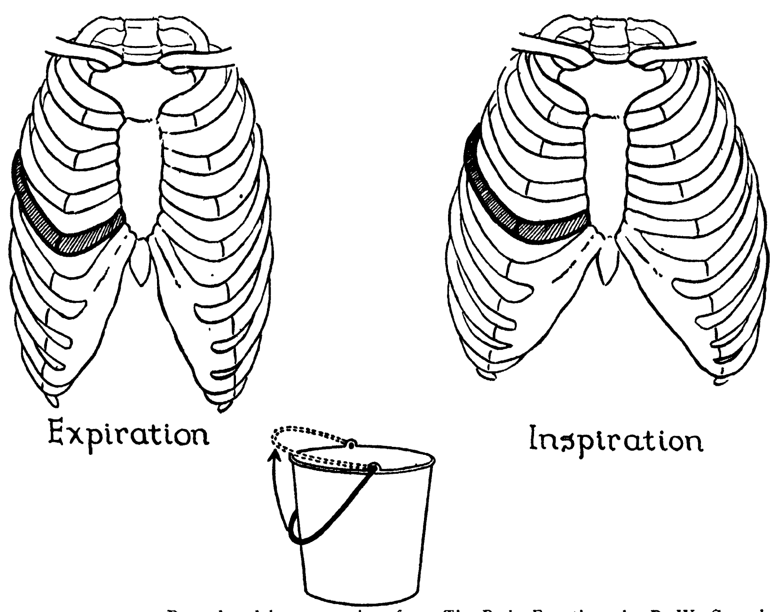


FIG. 223.—Structure of a small portion of the human lung. b, bronchiole; i, infundibulum; a, alveolus.

The pleural cavity has no communication with the outside atmosphere. Above and to the sides it is bounded by the body wall; and below the pleural cavity is walled off from the abdominal cavity by the *diaphragm*—a strong dome-shaped sheet of muscle tissue (Fig. 222). Pressure in the pleural cavity is generally negative (i.e., less than the pressure of the outside atmosphere)—because the elasticity of the inflated lung tends to pull the lung away from the thoracic wall, generating a partial vacuum in the pleural cavity. Thus to collapse a lung while it is still in the body—and this is sometimes necessary in severe tuberculosis—the surgeon merely punctures the thoracic wall. This operation permits air to flow directly into the pleural cavity, destroying the partial vacuum and allowing the lung to deflate itself as a result of its own elasticity.

Breathing Movements. Adequate aeration of the blood in the lungs depends upon an efficient ventilation of the alveolar air spaces; and in most animals the breathing movements go on very continuously. Each *inspiration* is quickly followed by an



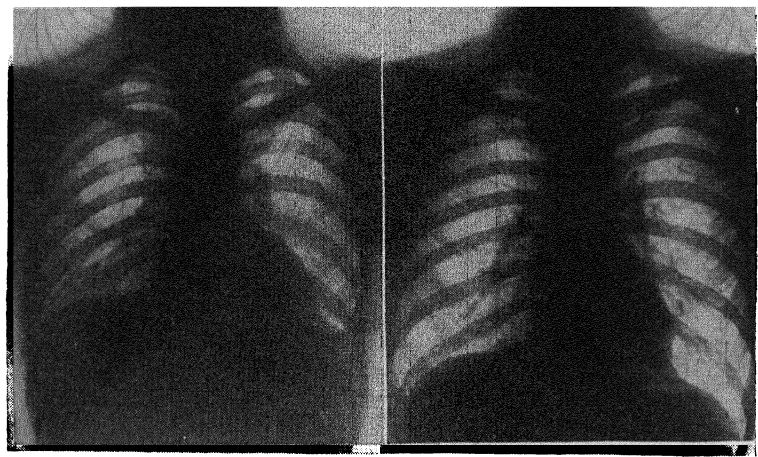
Reproduced by permission, from *The Body Functions*, by R. W. Gerard, published by John Wiley and Sons, Inc.

FIG. 224.—Each rib is attached to the spinal column behind and to the breastbone in front; and, like the handle of a bucket, moves outward as it is pulled up. In addition, the whole breastbone moves up slightly during an inspiration, so that the distance from vertebral column to breastbone is also increased. Finally, the downward movement of the diaphragm increases the third (vertical) dimension of the chest. (Drawn by E. M.)

expiration; and in man, these respiratory movements recur about 18 times per minute from birth to death.

Inspiration involves a co-ordinated contraction of a number of muscles; and expiration follows when the same muscles relax. The muscles most important in breathing are the diaphragm and the intercostal muscles. The action of these muscles is to broaden and deepen the thorax, increasing its cubic capacity (Figs. 224 and 225). The intercostal muscles raise the ribs and swing them

laterally, more or less like the handle of a bucket (Fig. 224); and simultaneously the dome-shaped diaphragm contracts, lowering the floor of the thorax (Fig. 225). Such an enlargement of the thorax increases the partial vacuum in the pleural cavity, and this suction is transmitted through the lungs to the outside air. Thus, as soon as the intrapulmonary pressure falls be-



Courtesy Roentology Staff, Billings Hospital. Reproduced by permission from *The Body Functions*, by R. W. Gerard, published by John Wiley and Sons, Inc.

FIG. 225.—Normal chest, at end of expiration (left); and at end of inspiration (right). Note that during inspiration: (1) the ribs and breastbone are elevated; and (2) the diaphragm and heart are depressed.

low that of the outside atmosphere, air passes into the lungs via the trachea and other passages.

Expiration usually involves just a reversal of these movements. The relaxing intercostal muscles allow the ribs to spring back to their former position; the diaphragm encroaches upon the thorax from below; and both these processes allow the lungs to expel the air which previously was inhaled.

Forced breathing also requires the cooperation of the abdominal muscles. At the apex of the fullest inspiration the diaphragm is greatly depressed. Thus considerable pressure would be exerted upon the abdominal organs, were it not for the fact that simultaneously there is a relaxation of the muscles of the

abdominal wall. Conversely, at the extremity of a forced expiration, the muscular abdominal wall clamps down, forcing the viscera to push the diaphragm as far as possible upward into the thoracic cavity. Likewise coughing and sneezing represent forced expirations which involve a vigorous contraction of the abdominal muscles. The resulting wave of pressure in the abdominal cavity is transmitted across the diaphragm to the lungs, and a draft of air is forced upward through the respiratory passages, clearing the trachea, pharynx, or nasal passages of irritating matter.

Volume Intake and Output of the Lungs. The lungs of man have large reserves to meet the demands of work and exercise. During sedentary activity, only about 500 cc. of air is swept into and out of the lungs each time we breath. But with the deepest inhalation it is possible to encompass an extra 2,500 cc.; and the strongest exhalation can put forth an additional 1,000 cc. of air. Thus a maximum exhalation following a maximum inhalation may deliver about 4,000 cc.; and this total represents the *vital capacity* of an individual. A trained athlete usually displays a relatively high vital capacity; although the physical stature and build of the individual must be taken into consideration. Certain diseases of the lungs and heart, on the other hand, may reduce the vital capacity below the standard of the age-sex-stature group to which the individual belongs.

About 1,000 cc. of air remains in the lungs at the end of the strongest exhalation. The trachea, bronchi, and bronchioles contain about 150 cc. of this *residual air*, and the remainder lies in the alveolar spaces. Even a collapsed lung, completely removed from the body, contains some air. Accordingly such a lung is sufficiently buoyant to float in water. This is not true, however, of the lung of a foetus, or of a stillborn child, which never has been inflated with air. Consequently the floating test is commonly employed by the medical examiner in cases of suspected infanticide.

Composition of the Alveolar Air. The aeration of the blood occurs entirely in the alveoli, and not in the larger air passages (trachea, bronchi, and bronchioles). Consequently it is

most important to determine the composition of the inspired air which reaches the alveolar chambers. Owing to the incompleteness of the ventilation of the deeper recesses of the lungs, the composition of alveolar air is somewhat different from that of the outside atmosphere. Inevitably there is some depletion of oxygen and accumulation of carbon dioxide in the alveolar air.

Of the 500 cc. of fresh air which is inhaled at each breath, about 150 cc. never reaches the alveoli but remains in the so-called "dead space" of the trachea, bronchi and larger bronchioles. Thus only 350 cc. reaches the alveolar chambers. Accordingly the new air is diluted by (a) the air which previously occupied the dead space and (b) the residual alveolar air. Thus the alveolar air is a mixture of "new" and "old" air in which the "old" predominates. An air sample collected at the end of a maximum forced expiration closely approximates the alveolar air; and the composition of alveolar air, compared with atmospheric air, is given in Table XVIII.

TABLE XVIII

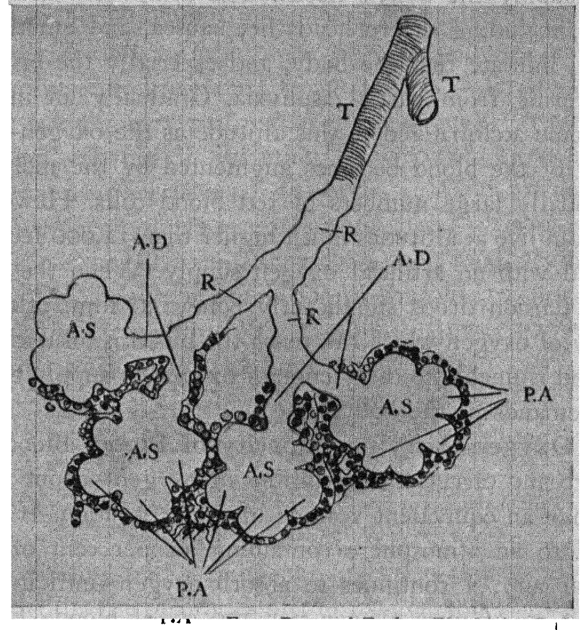
COMPARISON BETWEEN ATMOSPHERIC AND ALVEOLAR AIR

	Per Cent by Volume	
	Atmospheric Air (Dried)	*Alveolar Air (Dried)*
Oxygen	20.96	14.2
Carbon dioxide	0.04	5.5
Nitrogen (with argon)	79.00	80.3
Totals	100.00	100.0

Even though alveolar air is relatively poor in oxygen and rich in carbon dioxide, aeration of the blood in the alveolar capillaries proceeds on a strictly osmotic basis. If venous blood, such as passes to the lungs, is exposed directly to alveolar air, the blood absorbs oxygen and gives off carbon dioxide. In the lung the alveolar air is separated from the blood merely by the

exquisitely thin walls of the alveolus and capillaries (Fig. 226); and these membranes are so freely permeable to the respiratory gases that they cause little delay in the attainment of equilibrium.

Some early students of respiration believed that the alveolar walls could force oxygen into the blood, especially when the



From Best and Taylor, *The Living Body*

FIG. 226.—The close relation between the alveoli and the blood capillaries. A.D, alveolar ducts; A.S, air sacs; P.A, pulmonary alveoli; R, respiratory bronchiole; T, terminal bronchiole. Note the capillaries filled with red cells surrounding the alveoli.

concentration of oxygen in the alveolar air is abnormally low. However, no convincing evidence for this view has been obtained. At high altitudes—where the air is rarefied—the oxygen concentration in the alveolar air falls off despite the fact that the breathing becomes deeper and faster. At sea level the total atmospheric pressure approximates 760 mm. of mercury, of which about 150 mm. represents the *partial pressure* of the oxygen. In the alveoli where the proportion of oxygen is only ⅔ that of the outside atmosphere, the oxygen pressure therefore

is only about 100 mm. of Hg. Acute respiratory embarrassment begins to appear at about 14,000 feet. Here the outside atmospheric pressure falls to about 450 mm. of Hg, and the oxygen pressure in the alveoli is reduced to about 55 mm. of Hg. Now the blood passing through the lungs fails to absorb enough oxygen to supply the body's needs. The symptoms of *mountain sickness*, including severe headache, nausea, and emotional instability, indicate that the body, and especially the brain cells, are suffering from partial asphyxia. Gradually an individual can become acclimatized to this altitude as the oxygen-carrying capacity of the blood becomes augmented by the mobilization of unusually large numbers of red blood cells. However, no person can live at altitudes much higher than 14,000 feet, unless equipped with an artificial oxygen supply. When the alveolar oxygen tension drops significantly below 50 mm. of Hg, the quantity of oxygen which can reach the blood is insufficient, and the blood is unable to carry enough oxygen to supply the minimum demands of the body.

The Oxygen-Carrying Capacity of Blood. Blood is able to absorb and carry large quantities of oxygen—about 50 times more than an equivalent volume of saline solution. If blood is exposed to an atmosphere containing 14 per cent of oxygen (alveolar air), it continues to absorb oxygen until it contains about 20 cc. of pure oxygen per 100 cc. of blood. This high oxygen-carrying capacity of blood is mainly due to its content of *hemoglobin*, which is a very efficient respiratory pigment.

Only a small fraction (about 2 per cent) of the oxygen load of the blood remains freely dissolved in the plasma and in the protoplasm of the corpuscles. Most of the oxygen unites chemically with the hemoglobin in the erythrocytes. As fast as it diffuses into the corpuscles from the plasma, free oxygen continues to unite with hemoglobin until all of this pigment has become oxygenated. Consequently the plasma does not reach equilibrium with the alveolar air until the hemoglobin becomes saturated.

Hemoglobin vs. Oxyhemoglobin. About 90 per cent of the dry weight of each red corpuscle represents the complex

iron-containing protein pigment, *hemoglobin*. The chemical properties of this compound are admirably adapted to the role it plays as an oxygen carrier. In the presence of adequate concentrations of oxygen, hemoglobin combines with oxygen on a 1 : 1 molecular basis, forming *oxyhemoglobin*. Oxyhemoglobin has a bright scarlet color—in contrast to the dull purplish red of reduced hemoglobin. Consequently the color of whole blood alters considerably while it flows through the lungs and changes from an unaerated (venous) to an aerated (arterial) condition.

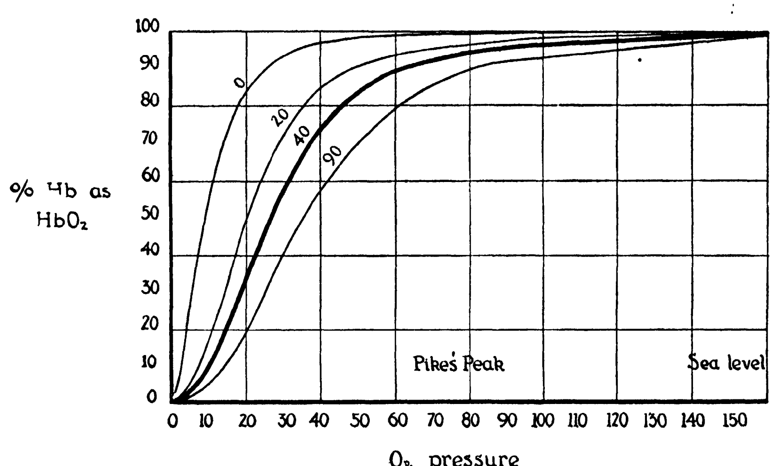
As a carrier of oxygen, oxyhemoglobin must be an unstable compound, capable of liberating free oxygen when the blood reaches the various tissues of the body. In other words the oxygenation of hemoglobin is a delicately poised *reversible* reaction. It shifts in either direction, depending upon small changes which occur in the chemical composition of the blood in the different parts of the circulation. This reaction, expressed in simplified equational form, may be written as follows:

$$\underset{\text{reduced hemoglobin}}{Hb + O_2} \; \underset{\substack{\text{at the tissues} \\ \text{low } O_2\text{, high } CO_2}}{\overset{\substack{\text{high } O_2\text{, low } CO_2 \\ \text{at the lungs}}}{\rightleftarrows}} \; \underset{\text{oxyhemoglobin}}{HbO_2}$$

The binding and freeing of oxygen in the blood is mainly controlled by the quantities of (1) oxygen and (2) carbon dioxide present in the different parts of the circulatory system—a conclusion (see Fig. 227) which is based on many experiments. In leaving the lungs, arterial blood remains isolated in the pulmonary veins and in the various arteries—until it reaches the capillaries in some other part of the body. Here the HbO_2 is exposed to an environment in which there is relatively little free oxygen—since the tissue cells consume oxygen—and here also carbon dioxide is abundant due to the continuous production of CO_2 by the tissues. Under these conditions (Fig. 227) HbO_2 liberates free oxygen, which then diffuses from the corpuscles, across the plasma and intervening membranes, into the tissue cells. Carbon dioxide, in contrast, continually diffuses in the opposite direction. Carbon dioxide passes from the cells, where

its concentration is maximum, into the blood. This gas exchange between the blood and the tissues is specified as *internal respiration;* and internal respiration proceeds spontaneously on an osmotic basis.

Venous blood, on leaving the tissues, likewise remains isolated in the veins and in the pulmonary arteries until it reaches the



Reproduced by permission, from *The Body Functions,* by R. W. Gerard, published by John Wiley and Sons, Inc.

FIG. 227.—The "oxygen dissociation curve" of hemoglobin is shown at four different carbon dioxide pressures, indicated above each curve. Carbon dioxide has a marked influence on the amount of oxygen with which hemoglobin will combine at any particular oxygen pressure; and this action of carbon dioxide is very important in the normal functioning of hemoglobin. The normal carbon dioxide pressure in arterial blood is a little over 40 millimeters, so that the heavy curve shows approximately the condition in blood. (Drawn by E. M.)

lung capillaries. Here the reduced Hb is exposed to the abundant oxygen of the alveolar air; and here also carbon dioxide begins to leave the blood by diffusing into the alveolar air spaces. Both of these factors favor the formation of HbO_2; and in the few seconds required for the corpuscles to file through the capillaries bordering the alveoli, practically all the hemoglobin is transformed to oxyhemoglobin.

The Carbon-Dioxide-Carrying Capacity of Blood. The water solubility of CO_2 is distinctly greater than that of oxy-

gen; but blood absorbs and carries more CO_2 than an equivalent volume of ordinary saline solution. In fact, if 100 cc. of venous blood is exposed to a vacuum, it gives up about 58 cc. of pure CO_2.

When it enters the blood from the tissues, CO_2 is transformed mainly into *bicarbonate* compounds. About ⅔ of the CO_2 is carried in the plasma, as sodium bicarbonate ($NaHCO_3$); and the other ⅓ is carried in the corpuscles, as potassium bicarbonate ($KHCO_3$). These bicarbonates remain stable while the blood is being carried to the lungs; but in the alveolar capillaries, the bicarbonates decompose, liberating the CO_2. The chemical reactions which liberate CO_2 from the bicarbonates are coupled with the oxygenation of hemoglobin. Just as the pouring in of CO_2 at the tissues favors the liberation of O_2 at the proper time, so the coming in of O_2 fosters the freeing of CO_2 at the lungs. Another main factor in the decomposition of the bicarbonates in the lungs is the reduction of the CO_2 concentration as this gas escapes into the alveolar spaces. Some of the details of these interlinked reactions are shown in Fig. 228. Very small changes in the concentrations of the gases in the different capillary regions act upon these chemical equilibria and determine the binding or freeing of each gas at the proper time and in the proper place.

Tissue Cells	*Blood Plasma*	*Red Corpuscles*
CO_2 —	→ CO_2 —	→ CO_2
	+	+
	H_2O	H_2O
	⇅	⇅
		H_2CO_3 $KHbO_2$
		⇅ ⇅
	$H_2CO_3 \rightleftharpoons HCO_3^- + H^+$ —	→ $H^+ + HbO_2^- \rightleftharpoons HHbO_2 \rightleftharpoons HHb + O_2$
		+ +
	+	$HCO_3^- + K^+ \rightleftharpoons KHCO_3$
		+
	$NaCl \rightleftharpoons Na^+ + Cl^-$ —	→ Cl^-
	⇅	⇅
	$NaHCO_3$	KCl
O_2 ←	— O_2 ←	—

FIG. 228.—Some of the chemical reactions between the respiratory gases and the components of whole blood, which occurs when CO_2 enters from the tissues. At the lungs, the O_2 coming in from the alveoli starts a reversal of these reactions.

Asphyxia. Any failure in the delivery of oxygen to the tissues, or in the usage of oxygen by the tissues, produces *asphyxia* in greater or lesser degree. Accordingly the causes of asphyxia may reside in the lungs, in the circulatory system, or in the tissue cells.

Pulmonary asphyxia may result from a displacement of alveolar air by water, as in drowning; or by an exudate of tissue fluid, as in pneumonia. When air cannot reach a large proportion of the alveoli, the quantity of oxygen absorbed and distributed by the blood is correspondingly restricted. Giving the patient pure oxygen helps—by augmenting the oxygen absorbed by the functioning alveoli; and in drowning, of course, an artificial ventilation of the lungs should be used if the asphyxia has abolished the normal respiratory movements. In asthma, there is a spasmic contraction of the muscles in the walls of the bronchi and bronchioles, which narrows these passages so drastically that they cannot conduct adequate air to the lungs.

Curtailment of the circulation—due to disorders of the heart or blood vessels—likewise curtails the delivery of oxygen to the tissues. *Carbon monoxide*, however, acts upon the circulation in a different way. Carbon monoxide, which is present in illuminating gas and in the exhaust fumes of gasoline motors, acts by blocking the capacity of hemoglobin to combine with oxygen. Hemoglobin unites with CO much more readily than with O_2; and the resulting cherry-red compound, HbCO, has no affinity for oxygen. In carbon monoxide asphyxia, therefore, the victim does not "turn blue," but appears "flushed" due to the color of carbon-monoxyl hemoglobin. Resuscitation from CO-asphyxia may be effected by artificial respiration, using an augmented oxygen supply—if available. Free Hb begins to be restored as soon as CO is removed from alveolar air; and this restoration occurs more readily when the O_2 pressure of the alveolar air is increased. In *anemia*, all the available hemoglobin may be oxygenated, but the amount of hemoglobin is so reduced that the blood does not carry enough oxygen to the tissues.

Respiratory poisons, such as cyanide, act primarily upon the tissues, rather than upon the blood. Cyanide, for example, blocks

cytochrome oxidase (p. 162) and perhaps others of the oxidizing enzymes of the cells, thus preventing a proper usage of oxygen in the tissues.

Control of Breathing. Active work may double, or even treble, the oxygen consumption of the muscles and other tissues; and this extra demand evokes a large increase in the depth and frequency of breathing, as well as an acceleration of the circulation. The *breathing reflexes* are integrated in the *respiratory center,* which is a specialized group of nerve cells situated in the *medulla* part of the brain (p. 602). The respiratory center is particularly responsive to *chemical conditions* in the blood which flows to this part of the brain, and these conditions may greatly modify the motor discharges of the respiratory center, which are sent to the diaphragm via the *phrenic nerves.*

Chemical Control of Breathing. The chief chemical factor controlling the activity of the respiratory center is the quantity of carbon dioxide present in the blood; and the respiratory center is extremely sensitive to changes in the CO_2 content of the blood. If, for example, the breathing is not fast and deep enough to prevent an accumulation of CO_2 in the alveolar air, CO_2 tends to accumulate in the blood. This stimulates the respiratory center, increasing the rate and depth of the breathing until the excess of CO_2 has been "blown off" from the lungs. Such an automatic control is very effective. An increase in the alveolar CO_2 from 5.5 to 5.7 per cent is enough to double the breathing rate; and a decrease to 5.3 per cent results in a temporary cessation of breathing. Thus after a series of very deep voluntary inhalations and exhalations, the alveolar CO_2 concentration is significantly reduced, and the subsequent breathing of the individual is usually suspended for about half a minute. Also the efficacy of 10 per cent CO_2, used to initiate the breathing of newborn infants, depends upon the stimulating effect of CO_2 upon the respiratory center.

The respiratory center is also sensitive, at least indirectly, to a diminution in the oxygen concentration of the blood. Thus breathing becomes faster and deeper whenever the aeration of the blood becomes inadequate. This oxygen control seems to be

indirect, however. Lack of oxygen leads to an accumulation of incompletely oxidized products such as lactic acid; and probably it is a slight increase of hydrogen ion concentration which stimulates the respiratory center.

A person cannot "hold the breath" beyond a certain relatively safe limit, because inhibitory impulses from the *cerebrum* (p. 592) are quenched at the respiratory center as soon as the chemical influences become strong enough to revive the rhythmic discharges of this center.

Nervous Control of Breathing. Sensory impulses from various receptors also modify the rhythmic motor discharges of the respiratory center (p. 602). At the crest of an inspiration, the stretching of the pulmonary wall excites the pressure receptors in the wall of the lung, and these receptors discharge a series of *inhibitory* impulses, which reach the respiratory center by way of the vagus nerves (p. 605). Conversely, at the depth of an expiration, other receptors in the pulmonary wall may send *excitatory* impulses, also via the vagus, to the central nervous system. Severe pain in any region of the body may act reflexly through the respiratory center—and the breath begins to "come faster." In swallowing, impulses from the pharyngeal receptors inhibit breathing for a moment—while food passes the glottis—and this prevents food from being sucked into the trachea and lungs. The gasp evoked by a plunge into icy water is also mediated through the respiratory center, as is likewise true of the coughing and sneezing reflexes. And last but not least, there is a group of special receptors situated in the wall of the *carotid sinus.* This bulbous swelling on the root of each internal carotid artery (p. 407) exercises an accessory control of the breathing and heart rates. The carotid sinus receptors are excited by increased carbon dioxide, and by decreased oxygen in the blood, and the sinus sends impulses to the respiratory center, fortifying its activity. All in all, therefore, the body has developed a number of checks and balances upon the breathing mechanism—for this system must be relied upon from the instant of birth to the moment of death.

TEST QUESTIONS

1. Differentiate between external and internal respiration. Why is it not possible to make such a distinction in very small organisms, like Hydra?
2. What is a specialized respiratory surface, and what advantages are provided by such a surface?
3. Differentiate between lungs and gills. Explain why gills are poorly suited to terrestrial conditions.
4. Explain the part played by the diaphragm and intercostal muscles in inspiration and expiration. How does a forced expiration differ from the expiration of ordinary breathing?
5. What is alveolar air? Explain how and why it differs from the external air.
6. Explain the term *partial pressure* of oxygen. Specify the partial pressure of oxygen: (a) in the outside atmosphere at sea level, (b) in the alveolar air at sea level, (c) in the outside air at 14,000 ft. elevation, and (d) in the alveolar air at 14,000 ft.
7. What are the symptoms of "mountain sickness"? What is the causation of this condition?
8. Compare the oxygen-carrying capacity of whole blood with that of (a) plasma and (b) salt solution. How is this difference to be accounted for?
9. Describe and explain the difference of color between venous (unaerated) and arterial (aerated) blood.
10. The binding and freeing of oxygen by hemoglobin is determined by the following equilibrium:

$$Hb + O_2 \leftrightarrows HbO_2$$

Explain how and why this equilibrium is shifted: (a) while the blood flows through the capillaries of the lung, and (b) while the blood flows through the capillaries of the other parts of the body.

11. Explain the mechanism of carbon monoxide asphyxia, specifying the best method of resuscitation.
12. Describe two other types of asphyxia, citing an example of each type.
13. Carefully explain how our breathing movements are modified by (a) chemical, and (b) nervous factors.

FURTHER READINGS

1. *Lessons from High Altitude*, by Joseph Barcroft; Cambridge, Eng., 1925.
2. *Respiration*, by J. S. Haldane; New Haven, 1927.
3. *The Wisdom of the Body*, by Walter B. Cannon; New York, 1939.

CHAPTER 19

EXCRETION

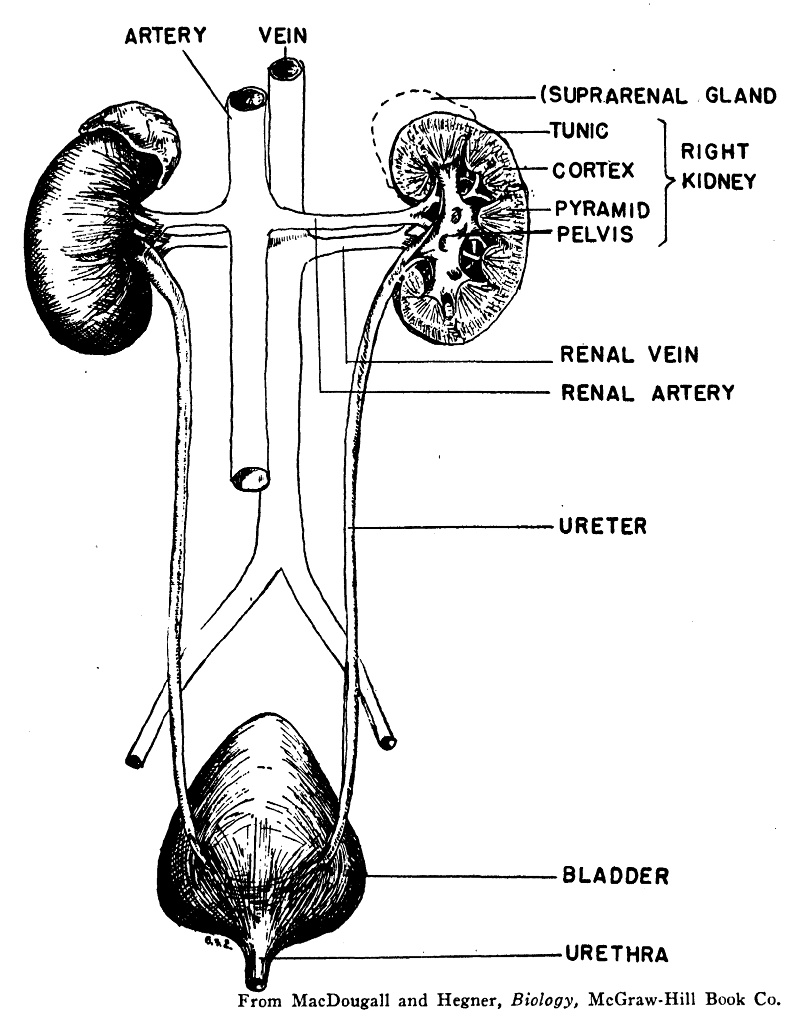
THE MAIN excretory organs of man and other vertebrates are the *kidneys* (Fig. 229). This pair of large bean-shaped organs is copiously supplied with blood, via the stout renal arteries. Night and day the kidneys work to rid the blood of *metabolic wastes*. Urea and other excretory wastes, which enter the blood all over the body, are eliminated as fast as they are formed; and normally these wastes never accumulate to toxic levels in the blood stream. Even with a single kidney, a man may get along quite safely; but if both kidneys are lost, the individual succumbs to *uremic poisoning* within a very few hours.

Excretory Processes in Lower Animals. Small and relatively simple animals, such as Protozoa and Coelenterates, eliminate their excretory wastes mainly by diffusion and osmosis. As soon as any metabolic end-product is produced in significant quantities in the cells, it begins to diffuse from this locus of higher concentration out into the environment, where the concentration is lower.

Water, however, presents a special problem (p. 157). Water is always an end-product of oxidative metabolism, and in fresh-water animals, water cannot diffuse out into the *hypotonic* environment. Consequently small fresh-water animals possess *contractile vacuoles*, or other mechanisms capable of performing *work* in forcing water out into the hypotonic environment.

An osmotic escape of excretory wastes becomes less and less adequate as the mass of an animal increases. In flatworms, such as Planaria, the body encompasses a considerable mass of meso-

dermal tissues, intervening between the ectoderm and endoderm. Such an increase in the mass of the body requires the



From MacDougall and Hegner, *Biology*, McGraw-Hill Book Co.

FIG. 229.—Diagram of the human urinary system, posterior view. (B. F. Edwards.)

development of specialized excretory organs, and Planaria possesses a large number of *flame-cells* (Fig. 230), scattered throughout the mesoderm. Each flame-cell is a hollow struc-

ture with a tuft of active cilia in the central cavity; and the beating of these accounts for the "flickering" which can be seen in a flame-cell, when it is viewed with a microscope. The many flame-cells on each side of Planaria are connected by a branching system of fine tubes to main *excretory ducts.* The excretory ducts run anteriorly on either side of the mid-line of the body, emptying through a series of *excretory pores,* on the dorsal surface of the animal.

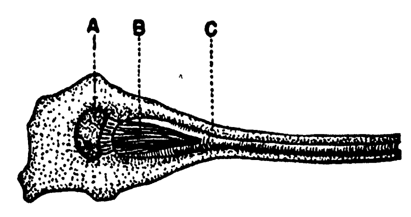


FIG. 230.—A flame cell, highly magnified. A—nucleus; B—tuft of cilia; C—excretory channel.

Precisely how the flame-cells function is not well understood. Apparently these cells extract water and other excretory wastes from the body fluid—which fills the tissue spaces of the mesoderm—and drive the resulting solution of wastes out of the body, via the excretory ducts.

In Annelids, such as the earthworm, the mesodermal tissues are much more abundant and highly differentiated; and also there is a well-developed blood system. The *excretory organs* of the earthworm and other Annelids are the *nephridia,* of which there are usually two in each *segment* of the body (Fig. 231). Each nephridium is a long highly coiled tube, which leads from the body cavity of one segment to the external surface of the succeeding segment of the body. At the coelomic end of the nephridium there is a ciliated funnel-shaped opening; and the lumen of the nephridium—throughout most of its length—is also lined with cilia. Moreover, there is a network of capillaries (not shown in the figure) which come into intimate contact with the glandular walls of the nephridium.

The functioning of the nephridial tubules has not been studied very adequately. However, the nephridia tend to resemble

the kidney tubules of higher animals (p. 475); and it may be supposed that they function in a somewhat similar fashion. The cilia maintain a flow of the body fluid—from the coelomic cavity, through the tubule, toward the external opening. The coelomic

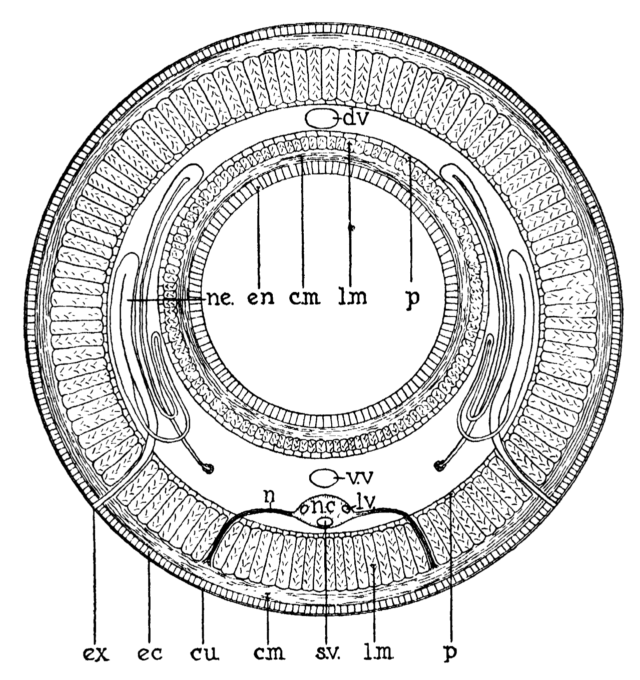


FIG. 231.—Earthworm, diagrammatic cross-section. ec, ectoderm; cu, cuticle (non-cellular layer secreted by the ectoderm); cm, circular muscles; lm, longitudinal muscles; p, peritoneum; en, endoderm; ne, *nephridium;* ex, excretory pore; n.c., nerve cord; n, nerve; d.v., dorsal blood vessel; v.v., ventral blood vessel; s.v., subneural blood vessel; l.v., lateral-neural blood vessel.

fluid contains glucose and other useful substances, as well as metabolic wastes, and probably the glandular cells in the wall of the nephridium—like the cells in the wall of a *kidney tubule* —extract glucose, water and other useful substances from the fluid while it passes toward the outside. In this way useful components of the body fluid are returned to the blood in the capillaries of the tubule; and waste products, due to a heavy reabsorption of water, are highly concentrated by the time the excretory fluid is voided at the surface of the body.

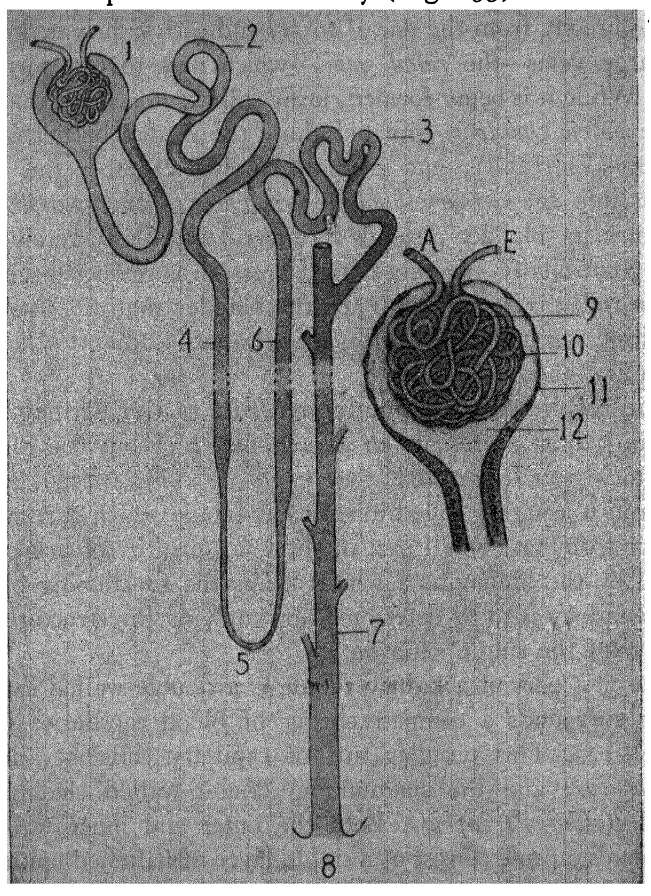
Structure and Functions of the Kidney. The work of the kidney is to extract urine from the blood which flows through it. Each kidney (Fig. 229) receives a major artery—the *renal artery*—directly from the *dorsal aorta;* and each kidney is drained by large veins—the *renal veins*—which pass to the *postcaval* vein. While it is being formed, urine collects in a small chamber —the *pelvic chamber*—situated along the medial border of the kidney (Fig. 229); and from the pelvic chamber the urine drains into the *urinary bladder,* via each of the two *ureters.* The urinary bladder distends its muscular walls to receive the urine; but finally—when a critical pressure is reached—the urination reflex is generated. Then the bladder contracts—voiding the urine through the *urethra,* a single duct leading to the outside (Fig. 229).

The Nephrons, or Functional Units of the Kidney. The human kidney represents an aggregation of about one million excretory tubules—called the *nephrons* (Fig. 232). Each nephron is a highly coiled microscopic tubule which is responsible for forming a small part of the total quantity of urine produced by the kidney as a whole. Thus the functioning of the whole kidney is to be determined by studying the structure and activity of the single nephron.

The first part of a kidney tubule is a double-walled capsule which surrounds a compact cluster of blood capillaries (Fig. 232, 9-12). This peculiar tuft of capillary coils is called a *glomerulus;* and the surrounding double-walled chamber is called *Bowman's capsule.* Both the outer and inner walls of Bowman's capsule consist of a single layer of flattened epithelial cells; and the inner wall adheres very intimately to the tufted glomerular capillaries.

The cavity of Bowman's capsule leads directly into the long lumen of the nephron which eventually leads into a *collecting tubule* (Fig. 232, 8). To reach a collecting tubule, however, fluid in Bowman's capsule must flow consecutively through (1) the *proximal* convoluted tubule, (2) the hairpin shaped, *loop of Henle,* and (3) the *distal convoluted tubule.* The walls of the kidney tubules are made up of a single layer of *glandular*

epithelium; and the different parts of the nephrons occupy characteristic positions in the kidney (Fig. 233). The collecting



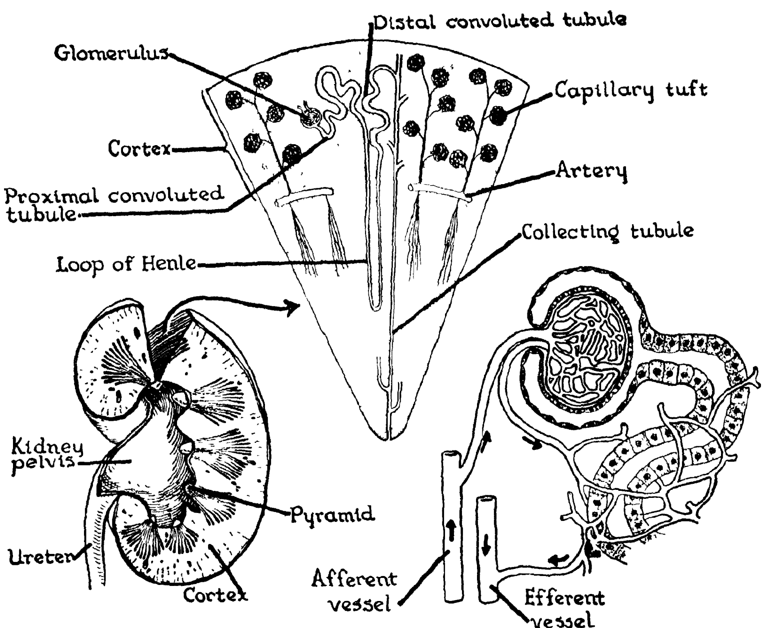
From Best and Taylor, *The Living Body*

FIG. 232.—The nephron. 1, glomerulus; 2, proximal convoluted tubule; 3, distal convoluted tubule; 4, descending limb of Henle's loop; 5, Henle's loop; 6, ascending limb; 7, collecting tubule; 8, pelvis of kidney. Enlarged drawing of glomerulus on the right; 9, tuft of capillaries; 10, layer of Bowman's capsule covering capillaries; 11, outer wall of Bowman's capsule; 12, cavity of Bowman's capsule; A, afferent arteriole; E, efferent arteriole.

tubules serve merely to drain the urine from the nephrons proper, into the pelvic chamber of the kidney.

The blood supply of the nephron is very important in deter-

mining kidney function. As may be seen in Fig. 233, each glomerulus is supplied by an *afferent vessel*, which is a branch of the renal artery; and each glomerulus is drained by an *efferent*



Reproduced by permission, from *The Body Functions*, by R. W. Gerard, published by John Wiley and Sons, Inc.

FIG. 233.—Diagram of the kidney (left), showing the general arrangement of cortex and pyramids. Above is a sector enlarged, with a single nephron (*with* its glomerulus, proximal convoluted tubule, long loop, and distal convoluted tubule) drawn in the center. On the sides are shown the blood vessels forming capillary tufts in many glomeruli, and their arrangement. On the right, a single glomerulus and the beginning of its tubule are drawn in greater enlargement and the details of their blood supply are indicated. Note that the arteriole entering the capillary tuft of the glomerulus is larger than the vessel leaving (suggesting that the volume of blood leaving the glomerulus is less than that entering), and that the outflow vessel breaks up into capillaries around the tubule before finally joining others to form regular veins. (Drawn by E. M.)

vessel. The efferent vessels, however, return to the renal vein by a very indirect route—through a network of capillaries which enmeshes all the tubular parts of the nephron. Thus a given sample of blood in passing from the renal artery to the renal vein, must flow through two sets of capillaries: (1) the capillary

coils of the glomerulus itself and (2) the capillary network which lies in intimate contact with the tubular parts of the nephron.

The Formation of Urine. Kidney function has been studied intensively for many years; and today, although some problems remain unsolved, the main issues have been defined quite clearly.

The work of the kidney involves three processes:

1. The glomerulus and capsule, working together, subject each sample of blood to a process of *filtration.* This process forms a fluid, the *nephric filtrate,* which passes into Bowman's capsule while a given part of the blood flows through the glomerulus.

2. The tubular parts of the nephron salvage very large quantities of water and smaller quantities of glucose and other useful compounds—by *re-absorbing* these substances from the nephric filtrate while it passes through the tubules toward the pelvic chamber. This process of *selective re-absorption* demands that the gland cells in the tubule wall transfer the re-absorbed compounds back into the blood in the capillaries surrounding the tubule.

3. The glandular parts of the nephron *augment* the quantity of some metabolic wastes in the nephric filtrate by extracting these wastes from the blood in the surrounding capillary net and passing the wastes into the lumen of the nephron.

Re-absorption and *augmentation* greatly change the composition of the *nephric filtrate* as this fluid drains through the nephron toward the collecting tubules. In fact the fluid as it reaches the collecting tubule can no longer be called the filtrate—it is the *urine.*

Filtration: Nature of the Nephric Filtrate. The glomerulus and Bowman's capsule together form a very effective *force-filter.* In filtering the blood the glomerular and capsular walls allow considerable quantities of water, glucose, urea and all other of the crystalloidal components of the plasma to escape from the blood into the capsule. However, all the more complex components of the blood, particularly the plasma proteins and

other *colloids* (and, of course, the corpuscles) cannot pass through the glomerular walls, and do not appear in the filtrate. These colloids remain in the blood as it leaves the glomerulus via the efferent vessel. Each sample of blood passes rapidly through a glomerulus; and while it is passing, it loses only a small fraction (about 1 per cent) of its volume. This fraction

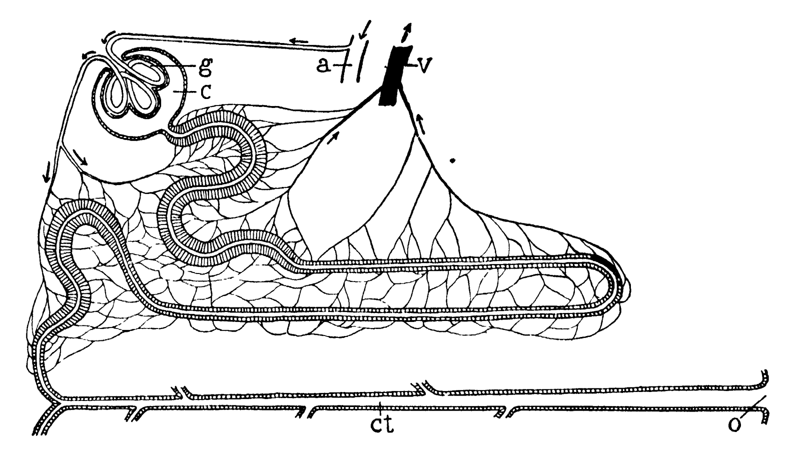


FIG. 234.—A single nephron, with its blood supply. Arrows indicate the direction of flow of the blood. a, artery; v, vein; g, glomerulus; c, capsule; ct, collecting tubule, into which a number of urinary tubules open; o, opening of collecting tubule to pelvis of the kidney.

becomes the filtrate, which is sidetracked into the nephric tubule; but simultaneously the main flow of blood continues, through the glomerulus and efferent vessel, and finally through the capillaries surrounding the other parts of the nephron (Fig. 234).

Determining the composition of the nephric filtrate is a very difficult task. The kidney of a frog, for example, can be exposed; and then a special microscope is used to examine the glomeruli and watch the nephric filtrate as it pours into the capsules of the nephrons. A very delicate glass syringe is required to withdraw samples of the filtrate from the capsules; and new micro-chemical methods were devised to analyze the extremely small samples of filtrate that were obtained.

Analysis of the capsular fluid (Table XIX) revealed essentially, that the nephric filtrate is a *colloid-free filtrate of the blood plasma.* The filtrate contains all the plasma crystalloids, including water, glucose, amino acids, and salts, as well as purely waste substances, such as urea and uric acid. Moreover the concentration of these crystalloids *is the same in the filtrate as it is in the plasma.* But the colloids of the plasma, mainly the proteins and lipoids, are held back. Under normal conditions no colloids are present in the filtrate as it enters Bowman's capsule.

TABLE XIX

THE NEPHRIC FILTRATE—AS COMPARED TO THE PLASMA AND URINE

Main Components	*Grams per 100 cc. of Fluid*		
	Plasma	*Nephric Filtrate*	*Urine*
Urea	0.03	0.03	2.0
Uric acid	0.004	0.004	0.05
Glucose	0.10	0.10	Trace
Amino acids	0.05	0.05	Trace
Total inorganic salts	0.72	0.72	1.50
Proteins and other colloids	8.00	0.000	0.00

The work of forcing filtrate from the blood into the capsule is done, not by the kidney, but by the heart. Blood pressure in the glomerulus must be maintained at a level above 30 mm. of mercury, if any filtrate is to be formed; and other factors being equal, the quantity of filtrate and urine formed in a given time tends to parallel the blood pressure.

The filtrate contains the same solutes as the plasma, except that the colloids of the plasma are lacking in the filtrate—and consequently filtrate is hypotonic to the plasma. Normally the glomerular blood pressure amounts to about 70 mm. of mercury. About 30 mm. of this pressure is expended in overcoming back-pressure—due to the hypotonicity of the filtrate—and only 40 mm. is the *effective pressure,* which drives more filtrate into

the nephric capsule. If the blood pressure rises or falls, the effective filtration pressure follows, and the quantity of filtrate varies accordingly.

Re-absorption. Normal urine (Table XIX) contains virtually no glucose or amino acids, because the convoluted tubules extract these useful compounds from the filtrate, and return them to the blood which flows through surrounding capillaries. However, the work of re-absorption is performed in a highly selective manner. Glucose, for example, is not re-absorbed if the blood already contains too much glucose. Thus the nephric tubules of a hyperglycemic subject do not re-absorb glucose, and the excess sugar remains in the filtrate and appears in the urine. Also the inorganic salts are re-absorbed selectively—according to their proper concentrations in the blood stream. Selective re-absorption reclaims many compounds from the filtrate—but only the proper amount of each different substance is reclaimed, and excess quantities are discarded in the urine.

In salvaging glucose, amino acids, and other substances from the filtrate, the tubules must perform *osmotic work.* Initially the concentration of glucose, for example, is equal in the filtrate and in the blood. Consequently there is no tendency for glucose to be re-absorbed spontaneously. The kidney cells derive the energy for this work from their oxidative metabolism; and if a kidney is deprived of oxygen (e.g., by treatment with cyanide), re-absorption quickly ceases. Such a kidney still forms urine—but the urine is extremely copious and dilute—possessing practically the same composition as the filtrate.

Re-absorption of Water. The salvaging of water from the nephric filtrate is a major kidney function. In fact the human kidney produces about a hundred liters of filtrate while it is forming just one liter of urine. In other words, the kidney usually re-absorbs about 99 liters of water in the process of forming one liter of urine; and if the kidneys lose their capacity to re-absorb water, they put forth very large volumes of highly dilute urine (p. 537).

The heavy re-absorption of water accounts mainly for the high concentrations of *urea* and other wastes which are found

in the urine. In fact any solute originally present in the filtrate becomes highly concentrated in the urine, unless this solute is re-absorbed while water is being re-absorbed. In the human urine, urea usually reaches a concentration about sixty times greater than in the blood plasma, and were it not for the fact that small quantities of urea are re-absorbed along with the larger quantities of water, this difference of concentration would be even greater.

The quantity of water re-absorbed by the human kidney varies quite widely, depending on the needs of the body. When large quantities of water are drunk, and while the blood tends to be diluted, the re-absorption of water remains at a minimum, and a large volume of dilute urine is formed by the kidney. But if the water intake is restricted, re-absorption reaches a maximum, so that the kidney conserves a maximum of water for the body.

The water re-absorbing capacity of the kidney is a good measure of an animal's capacity to conserve water. In aquatic and semi-aquatic vertebrates, especially fresh water fish and Amphibia, water re-absorption is not conspicuous, and such animals form large quantities of hypotonic urine. But in terrestrial vertebrates, the average quantity of urine is much reduced, and the urine is usually distinctly hypertonic as compared to plasma. In producing such a hypertonic urine the kidney performs definite *work,* which requires that the tubules must be supplied with adequate oxygen. When deprived of oxygen, the kidney loses its capacity to re-absorb water and produces a very large volume of highly dilute urine, regardless of the needs of the body.

Augmentation. Certain dyestuffs and perhaps some of the natural wastes seem to be transmitted from the blood in the capillaries surrounding the nephric tubule into the nephric fluid. Therefore, the total quantity of such substances in the urine represents the sum of two quantities: (1) the portion that filters into Bowman's capsule, and (2) the portion that is secreted into the tubule by the glandular walls. Such *augmentation* probably

plays only a minor role in normal kidney function. In fact, the evidence shows that a large proportion of the water which is filtered into Bowman's capsule is re-absorbed before the filtrate reaches the collecting tubule; and this accounts for most of the kidney's capacity to concentrate the excretory wastes.

Renal Impairments. Ordinary kidney disease, or *nephritis*, primarily involves the glomeruli. The diseased glomeruli become more freely permeable than normal; and in severe cases, the glomeruli show signs of disintegration. Normally the filtrate and urine are free of proteins; but in nephritis—first the plasma albumins, and then the more complex globulins, appear in the urine—depending on the severity of the case. In the severest cases, even intact erythrocytes are found in the urine. Owing to a continued loss of proteins, the capacity of the plasma to re-absorb fluid from the tissue spaces becomes impaired, and consequently edema usually develops (p. 421). In the terminal stages of nephritis the glomeruli cease to conduct blood and the filtration volume drops drastically. Then both water and excretory wastes accumulate in the body, and death from uremic poisoning becomes inevitable in about 24 hours, unless curative measures can be taken.

In *diabetes insipidus*, the patient's daily output of urine is 30 to 40 liters, instead of the normal average of about 1.5 liters. This condition represents a grave impairment of the water re-absorbing capacity of the tubules. The primary cause of diabetes insipidus is not localized in the kidney, however. The disease represents a failure of the pituitary gland to produce the *antiduretic hormone* (p. 537). Normally this hormone stimulates and controls the water re-absorbing activities of the tubules.

Chronic *hypertension*, or high blood pressure, is very frequently associated with nephritic impairments. The high pressure produces a very high filtration volume and injures the glomeruli. The kidney is not necessarily a passive factor in hypertensive cases. Recent work indicates that a normal function of the kidney is to produce one or more vasodilator substances—which tend to counteract high blood pressure. Also a kidney

with restricted circulation seems to produce a vasoconstrictor substance—called *renin*—which may aggravate the hypertension.

Summary. The function of the kidney is to maintain a normal blood composition by removing excesses of the various blood components and passing these substances into the urine. The kidneys differ from the lungs, in that not all the blood of the body passes through the renal vessels during each circuit. However, the large amount of blood which does pass through the renal circuit is cleared of all excess substances, and this clearance is adequate to prevent accumulation in the blood as a whole.

The important units of renal function are the nephrons, of which there are about a million in each kidney. The nephrons form the urine *mainly* by two processes—filtration and re-absorption. Each hour an average of about 6,000 cc. of colloid-free filtrate is forced into the capsular parts of the nephrons from the glomeruli, but only about 60 cc. of this fluid reaches the collecting tubules as urine. Meanwhile the volume is reduced, mainly by the re-absorption of water, but partly by the re-absorption of glucose, amino acids, and various inorganic salts. Each compound is reclaimed selectively, according to the concentration normally present in the plasma. In many cases re-absorption acts in opposition to the normal processes of osmosis, and in performing this definite work, the tubules expend energy and utilize oxygen. But, precisely how the cells of a tubule are able to force substances to move against a concentration gradient is still an unsolved problem. Most of the water appears to be re-absorbed in the loops of Henle and distal tubules; and most of the glucose is reclaimed in the proximal convoluted tubules. But the other functional differentiations of the various parts of the nephron remain obscure.

The urine is a remnant of the nephric filtrate, which retains most of the metabolic wastes as well as excesses of the other plasma components, such as inorganic salts and glucose. To a small extent, the initial quantity of certain wastes in the filtrate may be augmented by further quantities derived from the capillaries surrounding the tubule walls, but this type of activity does not appear to be very important in the human kidney.

TEST QUESTIONS

1. Specify the major metabolic wastes of man. What organs co-operate with the kidneys in eliminating these products? Explain.
2. Make a labelled diagram to show the human kidneys, the renal blood vessels, and the connections of the kidneys with the other parts of the excretory tract.
3. Make a labelled diagram to show all parts of a nephric tubule and the relations of the tubule to the blood system.
4. What is the *nephric filtrate?* How is it formed?
5. Carefully explain why the nephric filtrate is called (a) a forced filtrate; (b) a colloid filtrate.
6. To what extent is glucose present (a) in the filtrate and (b) in the urine? Carefully explain this difference.
7. To what extent is urea present (a) in the nephric filtrate and (b) in the urine? Carefully explain this difference.
8. Why is re-absorption described as a *selective* process? Explain carefully, using (a) glucose, and (b) water to exemplify the discussion.
9. In achieving re-absorption, the tubule cells perform work. Carefully explain the statement in terms of:
   a. the re-absorption of glucose;
   b. the re-absorption of water.
10. Assuming that the kidneys of a normal individual produce 100 cc. of urine per hour, approximately what would be:
    a. the hourly filtration volume;
    b. the quantity of glucose re-absorbed each hour;
    c. the quantity of urea present in an hourly sample of the urine?
11. Trace a given molecule of water through the kidney assuming:
    a. it does not enter the filtrate;
    b. it enters the filtrate and is re-absorbed;
    c. it enters the filtrate and is not re-absorbed.
12. After the injection of a certain dye into the blood stream of a dog, the concentration of the dye in the urine is found to be 125 times greater than in the filtrate. How might this observation be explained, knowing that the filtrate/urine ratio of the dog is 100/1?

13. Carefully explain each of the following conditions in terms of kidney structure and function:
    a. albumin in the urine;
    b. red corpuscles in the urine;
    c. glucose in the urine;
    d. an extremely copious dilute urine;
    e. virtually no urine.

FUTURE READINGS

1. *The Physiology of the Kidney,* by Homer Smith; New York, 1937.
2. *The Living Body,* by C. H. Best and N. B. Taylor; New York, 1944.
3. *The Secretion of Urine,* by A. R. Cushny; London, 1926.

CHAPTER 20

REPRODUCTION IN MULTICELLULAR ANIMALS

EACH kind of animal and plant must reproduce rapidly enough to compensate for the death rate of its population—or failing this—extinction is inevitable. Accordingly, the trail of evolution is strewn with thousands of extinct species, known today only by the fossilized remnants of their former being.

With few exceptions, multicellular animals reproduce sexually, although quite a few can also multiply asexually. Primary attention will be given to the sexual methods, with only a brief discussion of the asexual processes.

Reproductive Organs. Most multicellular animals possess well-developed gonads. These *essential reproductive organs* produce the *gamete cells,* which are destined to convey part of the protoplasm of each parent to the zygote and other cells of the next generation.

Typically the *testes,* or sperm-producing gonads, are distinct from the *ovaries,* which produce the eggs. However, in rare cases (e.g., certain clams), eggs and sperm are generated within the same gonad, although not usually at the same time.

One very simple type of gonad is possessed by Hydra (Fig. 235). During the sexual period this primitive animal develops both testes and ovaries, which, however, are merely *temporary* organs. The gonads first appear as small swellings at the surface of the body, the testes near the upper end, and the ovaries nearer the foot. Each gonad represents a local accumulation of *germ cells* (p. 617), covered externally by an ectodermal epithelium. In the testes (Fig. 235) the germ cells divide repeatedly, form-

ing a large number of very small flagellated sperm. Eventually these sperm escape into the surrounding water, when the epithelial wall of the ripe testes begins to disintegrate.

In the ovary (Fig. 235) the germ cells also divide several times; but in this case the resulting cells are actively amoeboid

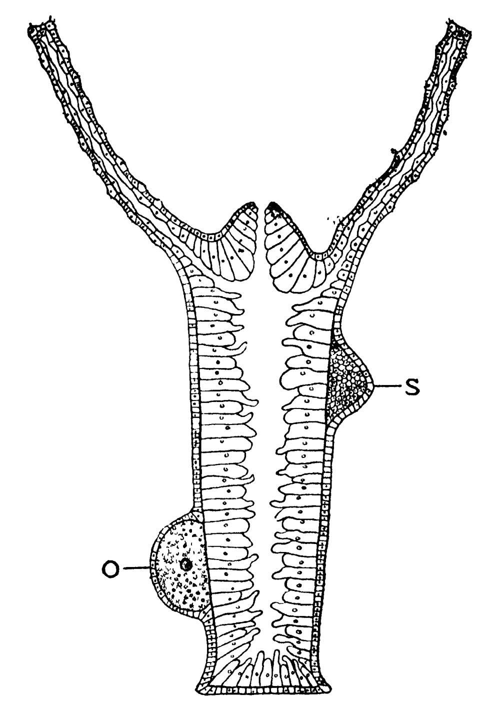


FIG. 235.—Sexually mature Hydra showing the temporary gonads. s, spermary; o, ovary.

and begin devouring each other in cannibalistic fashion. Finally only one hugely swollen cell remains, and this is the egg. Fertilization occurs after the epithelial wall of the ovary has disintegrated, and one of the free-swimming sperm chances to make contact with an exposed egg. Cross-fertilization is assured by the fact that the eggs and sperm of any one individual do not reach maturity simultaneously. Temporarily, while the egg is cleaving to form the blastula, the embryo remains attached to the body of the parent; but at about the time of gastrulation,

the offspring develops cilia and swims away as an independent *larva.*

The *monoecious* (*hermaphroditic*) condition, in which *both testes and ovaries are possessed by the same individual,* is not uncommon, especially among invertebrate animals; but on the whole, *dioecious* species, in which the *sexes are clearly separate,* greatly predominate. Also a vast majority of animals possess truly permanent gonads of greater or lesser complexity.

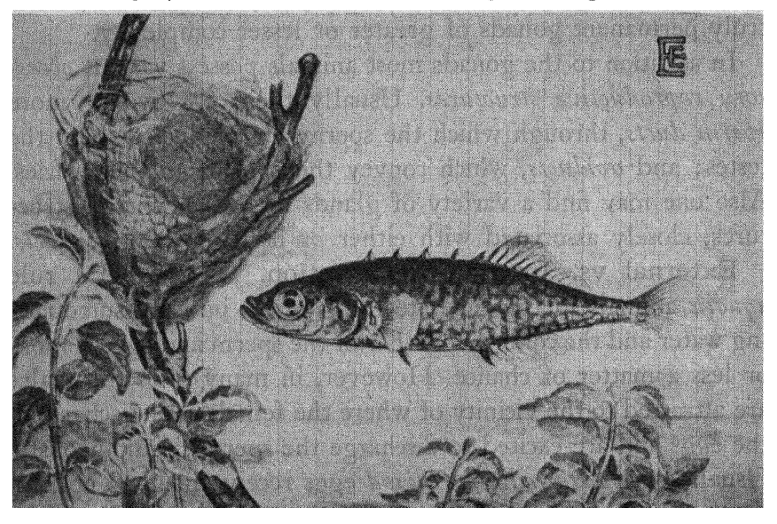
In addition to the gonads most animals possess various *accessory reproductive structures.* Usually there are two or more *sperm ducts,* through which the sperm are conducted from the testes; and *oviducts,* which convey the eggs from the ovaries. Also one may find a variety of glands and other special structures, closely associated with either or both of the *gonoducts.*

External vs. Internal Fertilization. As a general rule *aquatic* animals merely liberate the gametes into the surrounding water and the coming together of the sperm and eggs is more or less a matter of chance. However, in many cases the males are attracted to the vicinity of where the females are discharging the eggs and are excited to discharge the sperm simultaneously. Usually such *externally fertilized* eggs receive little or no parental care during development; but in some cases (Fig. 236) either or both parents may stand guard over the eggs. In some cases also the fertilized eggs become cemented to the body of one of the parents, which carries and protects the embryos during development.

Some essentially non-aquatic animals—such as many amphibia and insects—return to the water to lay their eggs, which may be fertilized either before or after discharge. Most terrestrial forms, however, ejaculate the sperm directly into the reproductive tract of the female, and thus fertilization occurs *internally.* Typically this process involves *copulation* between the sexes, and frequently the male is equipped with a *penis,* or some other type of *intromittent organ.* The *ejaculate,* or *semen,* includes not only the sperm, but also a greater or lesser amount of aqueous fluid secreted by the sperm ducts and associated glands. This fluid provides a suitable medium for the sperm

to swim in, and also contains nutrient substances to sustain the sperm until they make contact with the eggs.

In most cases a single copulation serves to fertilize only such eggs as happen to be mature at that time. However, the female reproductive tracts of some animals (e.g., many birds and insects) display one or more blind outpocketings, the *seminal*



Courtesy the New York Conservation Department

FIG. 236.—Male brook stickleback, guarding nest.

receptacles, in which the sperm collect and remain active for considerable periods after copulation. Thus the queen bee receives just a single visitation of the drone, and yet continues to deposit fertilized eggs for the rest of her reproductive life. Also the domestic hen may lay fertile eggs for a number of months after one contact with a rooster.

In some hermaphroditic animals, the copulating partners may mutually inseminate each other. For example, when earthworms copulate (Fig. 237), both individuals extrude semen from the sperm duct openings (segment 15). In each case the semen of one worm is guided into the other's seminal receptacles, two pair of blind pockets which extend inward from the ventral body wall in the 9th and 10th segments. Thus the net result of copu-

lation is that the seminal receptacles of each worm become filled with the semen of the other; and actual fertilization of the eggs does not occur until after the partners have separated. Then



FIG. 237.—Earthworms, copulating.

each worm secretes a broad beltlike cocoon around its *clitellum*, and starts wriggling backwards to escape from the encircling girdle. The eggs of the worm are extruded into the cocoon when this girdle has been displaced forward as far as the oviduct openings in the 14th segment; and the sperm (of the other worm) from the receptacles pass into the cocoon as soon as it

reaches the 9th and 10th segments. Finally, the worm wriggles entirely free of the cocoon, slipping it off over its tapered "head." Then the cocoon, which now contains fertilized eggs, seals itself by drying and twisting at the ends.

The Male Reproductive Tract of Man. In man and other vertebrates the reproductive tract, especially in the male, de-

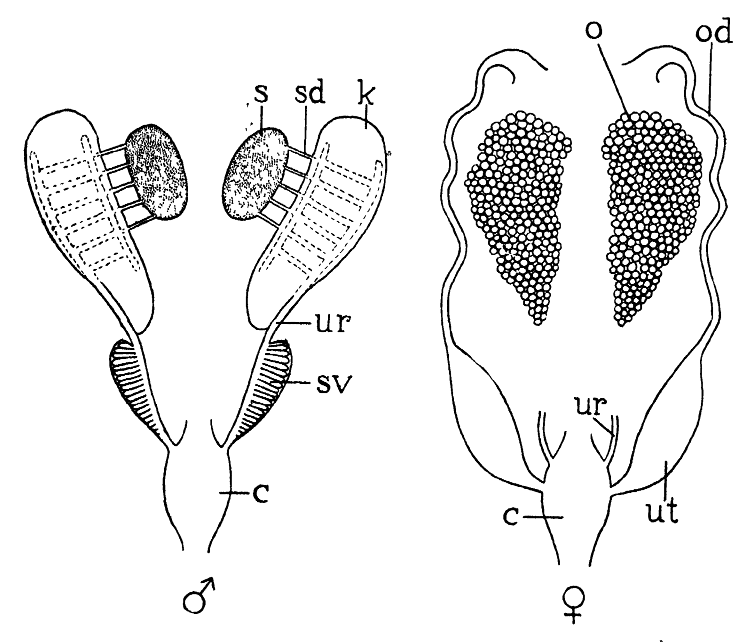
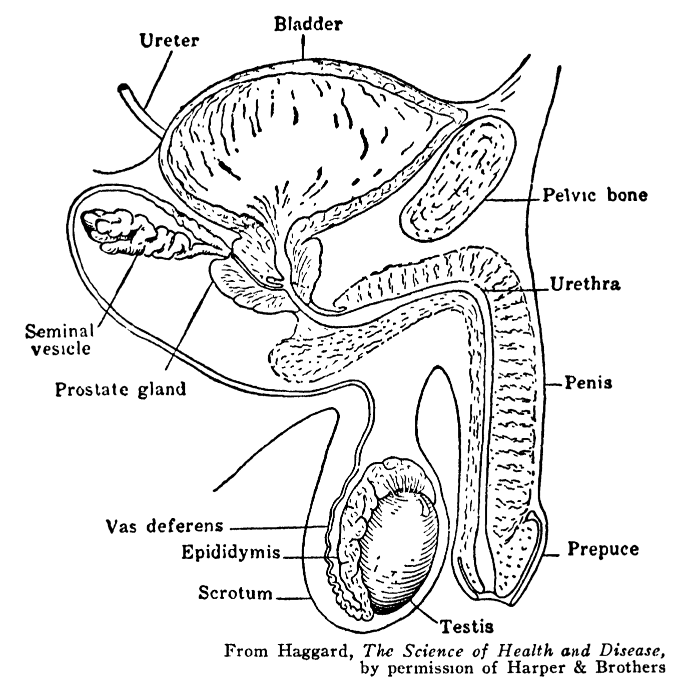


FIG. 238.—Diagrams of reproductive organs of male (♂) and female (♀) frog. s, spermary (testis); sd, spermiducts; k, kidney (dotted lines show the connections of the spermiducts with the ureter, within the kidney); ur, ureter; sv, seminal vesicle; o, ovary; od, oviduct; ut, uterus; c, cloaca.

velops in close association with the excretory system. Therefore the two systems together may be called the *urogenital system*. This association is mainly anatomical, however. Functionally the two sets of organs are quite separate, except that some of the ducts serve to transmit both genital and excretory products.

In vertebrates generally, the testes *originate* in the coelom just ventral to the embryonic kidneys; and in lower vertebrates, such as the frog, the adult gonads remain in this position (Fig. 238). But in man and many other Mammals the testes *descend*

shortly before or after birth, taking up a permanent position in the *scrotum* (Fig. 239). The scrotum, essentially, is an outpocketing of the body wall, which encloses a small portion of the original coelom. However, the *inguinal canal,* which originally is a free channel connecting the scrotal and abdominal



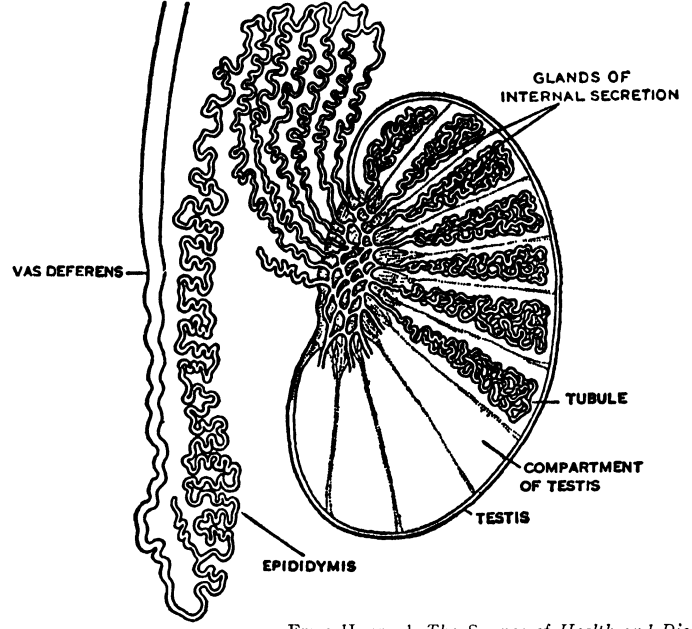
From Haggard, *The Science of Health and Disease,* by permission of Harper & Brothers

FIG. 239.—The genital tract (human male).

cavities, becomes blocked off by connective tissues. Thus in adults the scrotal and abdominal cavities are separate, except in cases of *inguinal hernia.* When herniation occurs, the original channel reopens; and in severe cases one loop of the intestine may be extruded into the scrotal sac. Rarely one or both testes may fail to descend into the scrotum, resulting in unilateral or bilateral *cryptorchy.*

Primarily the testis is a mass of highly coiled tubules, the *seminiferous tubules* (Fig. 240). These generate the sperm by

a multiplication of the germinal epithelial cells lining the walls (Fig. 241). Secondarily, however, the testis is an *endocrine gland*. Packed into the spaces between the tubules there is a considerable mass of *interstitial cells* (Fig. 241). This interstitial



From Haggard, *The Science of Health and Disease*, by permission of Harper & Brothers

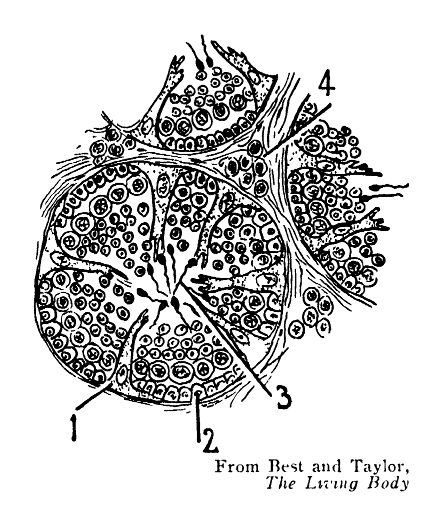
FIG. 240.—Human testis. Relations of the epididymis to the seminiferous tubules and vas deferens.

tissue produces the male sex hormone, *testosterone*, which is concerned with the development of the *secondary sexual characteristics* of the male (p. 517).

In the frog and most other lower vertebrates, the sperm pass through the kidney before they reach the main gonoduct (Fig. 238). A number of fine ducts, the *vasa efferentia*, lead from the testis to some of the *nephric tubules* in the kidney; and these nephric tubules drain into the *urogenital canal*. Moreover, the urogenital canal does not lead to the exterior, but drains into

the *cloaca.* This terminal portion of the digestive tract transmits the sperm, through the *anus* to the environment.

In man the sperm tract is very complex. There are a number of *vasa efferentia,* which carry the sperm into the *epididymis* (Fig. 240), a part of the genital tract which is derived from the embryonic kidney. The epididymis in man has the appearance of a compact mass which half encircles the testis (Fig. 239); but actually the epididymis is a very long (about 20 feet), much-coiled tube which leads finally into the *vas deferens,* or sperm duct proper. The vas deferens is a relatively simple tube, with a thick muscular wall, which leaves the scrotum and passes into the abdominal cavity, through the inguinal canal. In the abdominal cavity, the vas deferens ends by joining the *urethra,* a short stout tube that originates from the *urinary bladder.* Thus the urethra fulfills a double duty, in that it conveys both urine and semen to the extremity of the penis (Fig. 239).



From Best and Taylor, *The Living Body*

FIG. 241.—Cross-section of a sperm-forming tubule of the human testis (semi-diagrammatic). 1, cells of Sertoli; 2, spermatogonia; 3, mature sperm; 4, interstitial cells.

In addition to the sperm tract proper, the male reproductive system includes three pairs of glands. A large *seminal vesicle* drains into the vas deferens on each side, near the point where the sperm duct joins the urethra (Fig. 239); and the *prostate glands* empty into the urethra. In many mammals the *prostate* is plainly a double gland; but in man it appears as a single mass encompassing the root of the urethra (Fig. 239). The prostate secretion enters the urethra by two sets of fine ducts which come in from either side of the mass. And finally there are *Cowper's*

glands, a small pair of glands which empty into the urethra more distally.

The composition of the semen is very complex. In addition to the sperm, semen contains numerous glandular secretions; but the precise origin of these secretions is somewhat obscure. Probably some components of the semen are derived from the epithelium of the epididymis; and until the sperm have passed through the epididymis they never become motile. In fact the sperm do not gain full motility until they make contact with the secretions of the seminal vesicles; and the sperm tend to be swept through the vas deferens by peristaltic waves occurring in the wall of this muscular duct. The sperm tend to accumulate in the *ampulla*, a swollen part of the vas deferens, near the point where it receives the secretions of the seminal vesicle. The vesicular secretion provides an ideal medium for exciting and sustaining the swimming activity of the sperm. This fluid is well buffered with inorganic salts, and contains an unusually high concentration of glucose, which the sperm utilize in their metabolism. However, the metabolism of the sperm appears to be largely anaerobic. Sperm decompose glucose only as far as lactic acid and thus they utilize only a small fraction of the potentially available energy.

The secretions of the prostate and Cowper's glands are less clearly understood. During sexual excitement these fluids appear to precede the sperm through the urethra, and possibly the secretions are purely lubricatory in function.

As it traverses the penis, the *urethra* is flanked on all sides by *erectile tissue*, disposed in stout columns, called the *corpora cavernosa* (Fig. 239). This spongy tissue is permeated with blood sinuses; and ordinarily, when the sinuses are not distended with blood, the tissue is flaccid. But one of the reflexes in the pattern of sexual excitation leads to a constriction of the vessels that drain the sinuses. At this time, therefore, the erectile tissue becomes turgid and distended with blood; and temporarily the penis becomes an effective intromittent organ. When ejaculation occurs, the urethra is swept by a short but powerful series of peristaltic contractions.

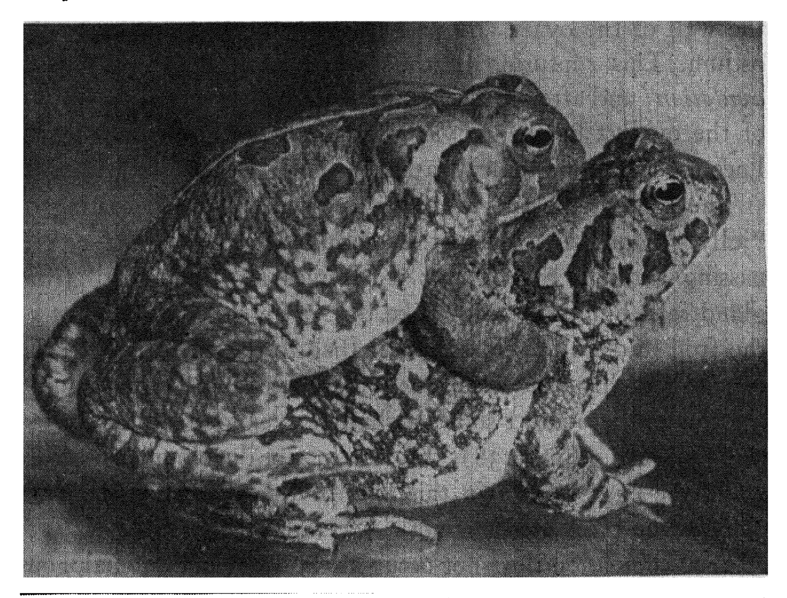
The Female Reproductive Organs. The *ovaries,* in vertebrate animals, are not connected directly with the oviducts. In the frog, for example, each large ovary, or *egg mass,* lies in the body cavity, ventral to the corresponding kidney (Fig. 238). The *ostium,* or dilated mouth of the oviduct, opens directly into the body cavity in a region somewhat anterior to the ovary (Fig. 238). To be liberated, therefore, the eggs must break through the wall of the ovary and pass through the body cavity to the ostium. This rupturing of the ovarian wall is referred to as *ovulation;* and after ovulation the eggs are carried to the mouth of the oviduct by the activity of the ciliated epithelium which lines the whole peritoneal cavity.

The eggs of the frog do not possess any external coating of "jelly" before they enter the oviduct; but while the egg is passing through the oviduct it receives its "jelly-coat" from gland cells lining the wall. Like the sperm duct, the oviduct of the frog leads to the cloaca rather than to the exterior; and the eggs are finally voided through the anus. Just before joining the cloaca, the oviduct shows a slightly expanded section, called the "uterus" (Fig. 238). However, no development occurs while the eggs remain in this part of the oviduct, and consequently the term uterus is not a very apt one.

True copulation does not occur in the frog, but an analogous reaction, called *amplexus* (Fig. 242) takes place about 24 hours before the female starts to shed the eggs. Amplexus continues until all the eggs have been extruded into the water; and simultaneously the male continues to liberate a stream of sperm while the eggs are issuing forth.

The Human Ovary and Its Functions. In the human female, as in other vertebrates, the ovaries have no direct connection with the oviducts, or *Fallopian tubes.* The human ovary —in size and shape—resembles a shelled almond (Fig. 243); although in older individuals the ovarian surface is roughened and pocked with numerous scars. These scars result from a repeated rupturing of the ovarian wall during successive ovulations.

The human ovary usually produces only one egg during each 28-day cycle of activity. The egg cell arises from the germinal epithelium of the ovary (Fig. 244). This epithelium proliferates periodically, forming a group of cells which is pushed inward from the surface of the ovary and finally pinched off as a separate mass (Fig. 244). This mass represents an incipient



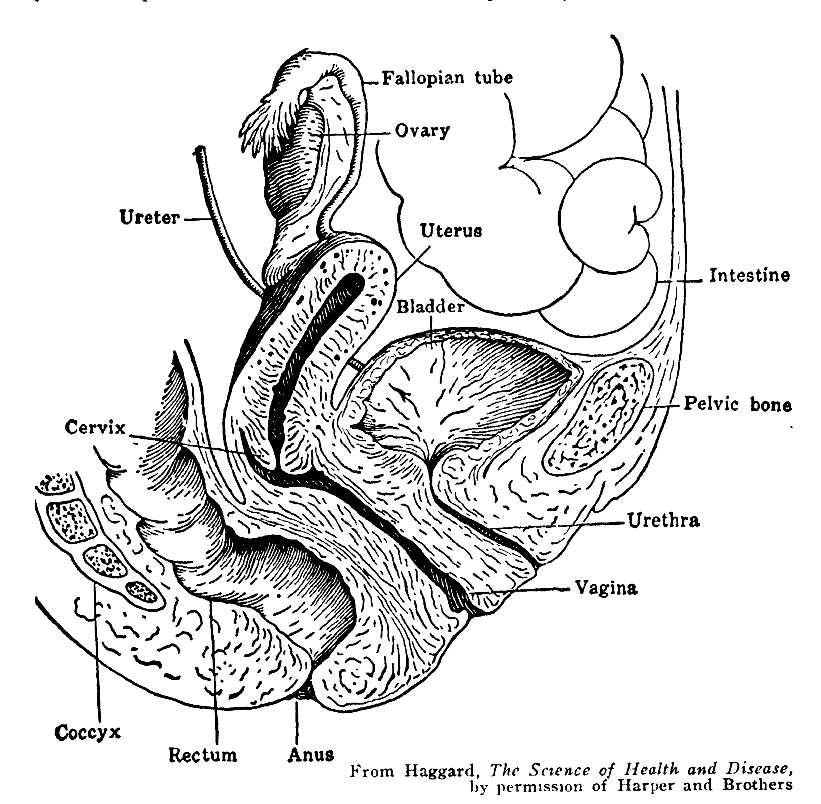
Courtesy of Dr. Roberts Rugh

FIG. 242.—Amplexus, in toads.

Graafian follicle, which soon becomes organized into a vesicle, enclosing the maturing egg (Fig. 244). The Graafian follicle continues to enlarge until it protrudes slightly from the surface of the ovary. Then, finally, when the egg is ripe, the follicle ruptures, discharging an egg near the mouth of the Fallopian tube. This process of *ovulation* occurs periodically in the human female, usually at a fixed time in relation to the menstrual cycle (p. 520).

The ovary has also developed two important endocrine functions, which are associated mainly with the Graafian follicles. As each follicle ripens, it becomes filled with a *follicular fluid,*

which contains the "female sex hormone," *estrogen* (p. 519). Estrogen has a profound effect upon bodily development, especially in regard to the *secondary sexual characteristics of the female* (p. 519). Before the time of *puberty*, none of the fol-



From Haggard, *The Science of Health and Disease*, by permission of Harper and Brothers

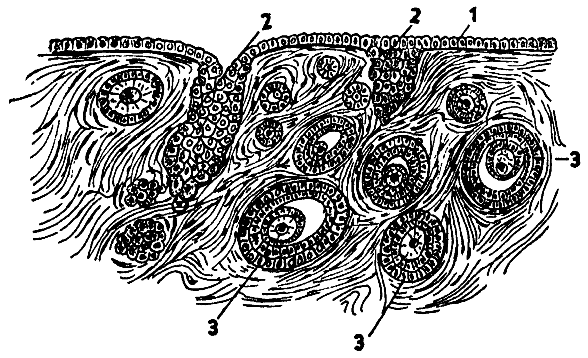
FIG. 243.—Genital tract (human female).

licles develops; and the features peculiar to womanhood are not very clearly differentiated.

The other endocrine function of the ovary is likewise associated with the Graafian follicles. *Subsequent* to ovulation, each follicle undergoes a considerable change of structure. The cavity of the follicle first becomes filled with a small clot of blood, the *blutpunkt;* but the blood is soon replaced by a mass of *yellow tissue*, derived from the inner lining of the follicle. This

yellow body is the *corpus luteum*, an endocrine gland which produces *progesterone*, the so-called pregnancy hormone (p. 522).

The Oviducts, Uterus and Vagina. The anatomical features of the other parts of the female reproductive tract are shown in Fig. 243. The *uterus* is a pear-shaped thick-walled muscular chamber, lined internally with a richly vascular mucous membrane. On each side of the upper margin, the uterus receives a Fallopian tube; and below and centrally, the uterus communi-



From Best and Taylor, *The Living Body*

FIG. 244.—Section of ovary. 1, germinal epithelium; 2, downgrowth of germinal epithelium; 3, Graafian follicles; stages of development.

cates with the *vagina*. The *cervix*, or lower tapered portion of the uterus, protrudes somewhat into the vaginal canal, which, like the uterus, has a muscular wall lined internally by a well-defined mucosa. Except in pregnancy, the uterus is scarcely larger than a closed fist; but during pregnancy the uterus enlarges to accommodate the growing *foetus*.

Fertilization; Implantation of the Embryo. Shortly after ovulation, the egg finds its way into the ostium of the Fallopian tube, which bears a fringe of ciliated outgrowths, surrounding the mouth of the oviduct (Fig. 243). Meanwhile, if copulation has occurred recently, sperm will probably have succeeded in leaving the vagina, traversing the uterine cavity and reaching the lumen of the Fallopian tube. Unless fertilization occurs before the egg leaves the oviduct, *pregnancy* rarely, if ever, takes place.

Granting fertilization, the first cleavages of the egg occur in the oviduct; but soon the young embryo descends into the uterus. Here the embryo stimulates the uterine wall, and the maternal tissues begin to surround and embed the embryo. As a result of this *decidual* reaction, the embryo becomes firmly *implanted*. After successful implantation, development continues at the expense of substances absorbed from the maternal blood stream. At the end of about 6 weeks the embryo measures almost an inch in length; and thereafter it is called a *foetus*. The foetus grows gradually, attaining a length of about 3 inches at 3 months; 10 inches at 5 months; and 20 inches at 9 months. The *gestation period* in man is about 10 lunar months (approximately 9 calendar months), whereupon the foetus is delivered through the vaginal passage.

Nutrition of Vertebrate Embryos. The problem of sustaining the metabolism of the embryo during the developmental period is relatively simple in the case of the lower vertebrates (e.g., fish and Amphibia) which deposit their eggs in *water*. Such eggs invariably contain a large amount of yolk materials, including protein, lipid and carbohydrate reserves; and these substances are gradually mobilized and used by the cells of the embryo as they multiply, grow and differentiate. Before it is used up, most of the yolk comes to lie in the *yolk sac*, a pouch-like extension of the embryonic enteron (Fig. 245). The walls of this embryonic nutritive organ become highly vascularized at an early developmental stage; and the stored food materials begin to be absorbed and distributed as soon as circulation is established. The embryo is surrounded by aerated water, from which the blood absorbs oxygen, and to which it gives off carbon dioxide and other waste products of metabolism.

Development in the Land-dwelling Vertebrates. The reptiles and birds were among the earliest terrestrial vertebrates, and these animals retained the *oviparous* (egg-laying) habits of their aquatic ancestors. Eggs laid on land, however, are always covered by a shell and other protective *membranes*; otherwise the developing embryos could not survive the drying effects of the atmosphere. Moreover, the embryos of land ani-

mals reach a relatively high state of development before they are able to face the hazards of the land environment. Accord-

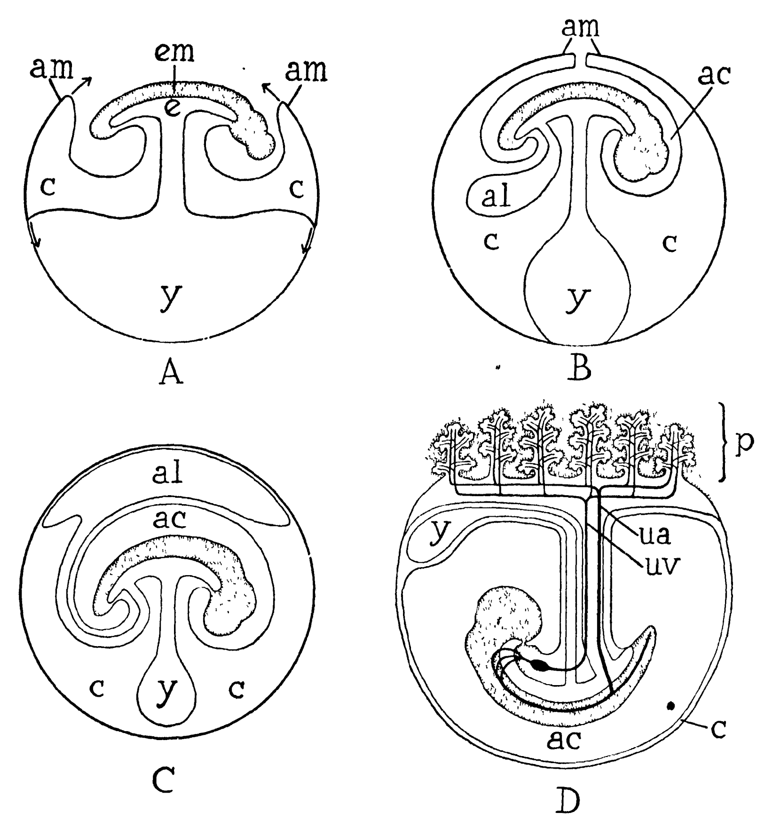


FIG. 245.—Development of the embryonic membranes and placenta. A, amnion growing out around the embryo; B, amnion about to close, allantois growing out into the extra-embryonic coelom; C, amnion complete, allantois fusing with outer wall of the extra-embryonic coelom; D, placenta fully developed. em, embryo; e, enteron; y, yolk sac; am, amnion; c, extra-embryonic coelom; ac, amniotic cavity; al, allantois; ua, umbilical artery; uv, umbilical vein; p, placenta, its maternal portion shaded (maternal blood vessels not shown), embryonic portion unshaded, with embryonic blood vessels indicated.

ingly, the egg cells of birds and reptiles, besides containing relatively large amounts of yolk, are surrounded by an "egg-white." This albuminous fluid provides the developing embryo with an extra reserve of water and additional protein reserves.

Both the "egg-white" and the calcareous shell are secreted by the glandular walls of the oviducts, after ovulation has occurred—while the egg is passing through the oviduct.

The Embryonic Membranes. In reptiles, birds and Mammals, embryonic development proceeds in the absence of the age-old aquatic environment; and such development involved the evolution of a highly specialized system of *embryonic membranes.* These arose in the form of the *amnion* and the *allantois,* a pair of living membranes which grow out from the embryo, enveloping it completely. Jointly these membranes protect the embryo; they also sustain the embryo by absorbing oxygen and other food and by eliminating metabolic wastes during the extended period of development.

The Amnion. The amnion, as it first appears, is an outfolding of the *body wall* of the embryo, which carries with it an extension of the *coelomic cavity* (Fig. 245, A). This double membranous fold continues to grow until it envelops the embryo completely (Fig. 245, B). Then the amniotic folds *meet* and *fuse* above the embryo, forming a new cavity, which is called the *amniotic cavity.* This amniotic cavity lies between the embryo and the inner layer of the amniotic fold, and is not to be confused with *extra-embryonic coelom,* which lies between the inner and outer folds of the original outgrowth. After the amniotic folds meet and fuse above the embryo, the inner layer of the outgrowth is called the *amniotic membrane,* and the outer layer is called the *chorion* (Fig. 245, C).

The amniotic cavity is filled with an aqueous fluid secreted by the amniotic membrane. Accordingly the embryo continues development suspended in a watery medium, which duplicates many of the conditions of a truly aquatic environment. In eggs of the birds and reptiles, the chorionic layer of the amniotic fold comes to lie in contact with the inner surface of the egg shell (Fig. 246). But in higher Mammals, the chorion comes into direct contact with the uterine wall which, after implantation, envelops the whole embryo.

The *allantois,* or second embryonic membrane, arises as an outpocketing from the *enteron.* As it grows the allantois con-

tinues to push out into the extra-embryonic coelom, especially in a posterior direction (Fig. 245, B-C). Then the outer layer of the allantois fuses intimately with the chorion, forming a single highly vascular membrane which lies immediately subjacent to the egg shell (Fig. 246).

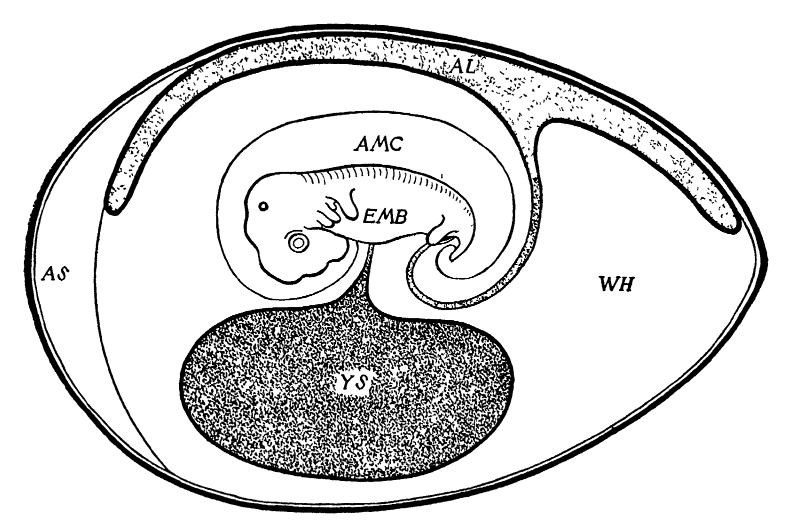
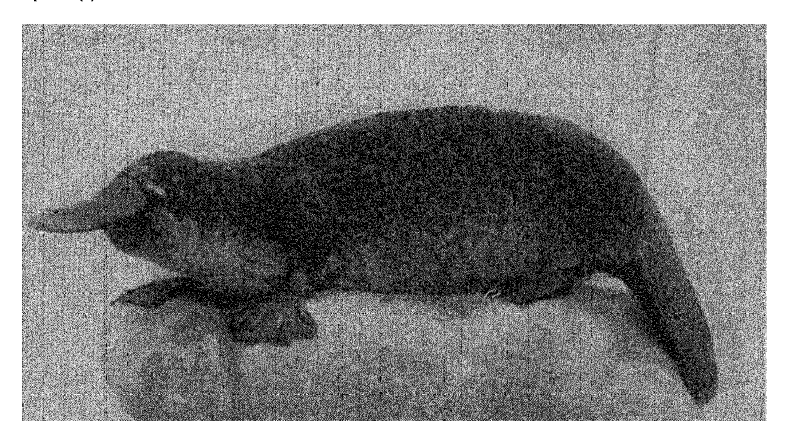


Fig. 246.—Embryonic membranes of the developing bird's egg. The heavy outer line represents the "shell." AL, allantois; AMC, amniotic cavity; EMB, embryo; YS, yolk sac; WH, remnant of the "egg-white"; AS, air space.

The allantois is an embryonic organ which fulfills the absorptive, respiratory and excretory needs of the developing embryo. Shortly after its formation, the allantois becomes permeated with blood capillaries which are supplied and drained by major vessels from the embryo proper. In the bird and reptile, the allantoic capillaries serve not only to take in oxygen and give off carbon dioxide through the porous shells, but also to absorb the material of the egg-white. Moreover, the allantois is a repository for the non-gaseous metabolic wastes which are formed during embryonic development. At the time of hatching, most of the allantois is discarded, together with all of the amnion. But the root of the allantois, at its junction with the

enteron, is retained and converted into part of the *urinary bladder* of the adult.

The Uterus and Placenta. The *Monotremes*, an almost extinct group of very primitive Mammals, have retained the oviparous habit (Fig. 247); but a great majority of present-day Mammals are *viviparous*. In such Mammals the developing offspring are retained within the uterus of the female until the end



Courtesy of the American Museum of Natural History, New York

FIG. 247.—The duckbill, one of the few surviving species of Monotremes. This primitive egg-laying Mammal has a birdlike bill and webbed feet.

of the embryonic period, and the embryos are nourished during the developmental period by food substances derived from the maternal blood stream. Essentially the uterus is a specialized portion of the oviducts (Fig. 248), which in some Mammals, like the rabbit, remains *duplex*, but in others, like man, becomes *simplex*.

The efficiency of the uterus—as an abode for the developing embryo—hinges upon the development of another structure, the *placenta*. This important nutritive organ is derived partly from maternal tissues which grow around the embryo when it becomes implanted in the uterine wall, and partly from the tissues of the embryonic membranes.

In higher Mammals, the chorion and allantois arise in much the same fashion as in reptiles and in birds; but in Mammals

the chorion comes into contact with the tissues of the uterine wall (Fig. 245, D), rather than with the inner surface of the egg shell. Moreover, the chorion sends out a large number of fingerlike outgrowths, the *chorionic villi*, which penetrate deeply into the uterine wall (Fig. 249). This region, where the tissues of the chorion and uterus are intermingled, is the *placenta*, which permits osmotic exchanges to occur between the blood of the

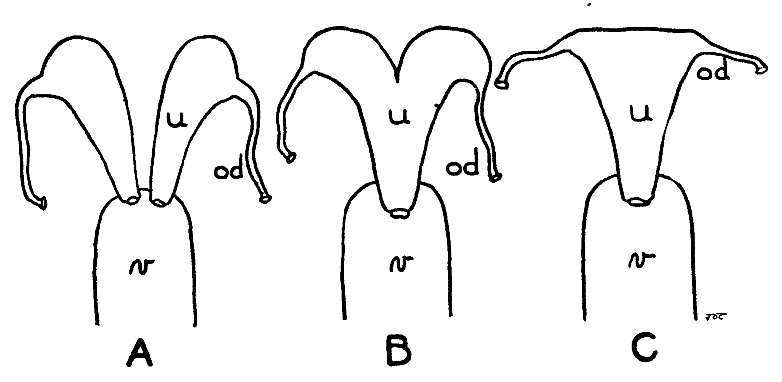
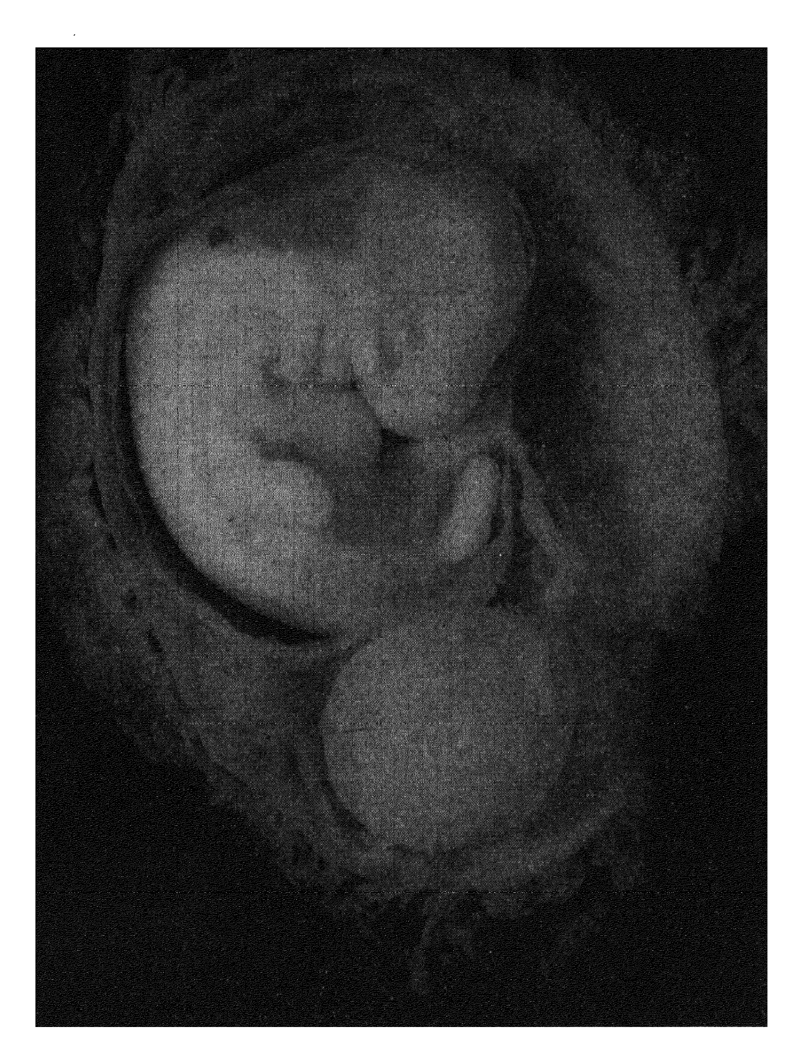


FIG. 248.—The uterus developed as a specialized part of the oviduct. Types of uteri in various Mammals. A, duplex type (as in the rabbit); B, bicornuate type (as in the cat); C, simplex type (as in man). u, uterus; od, oviduct; v, vagina.

foetus and that of the mother. The *chorionic villi* are richly supplied with blood capillaries, derived from the *umbilical artery*. This large artery extends out from the embryo along the stalk of the allantois; and the chorionic capillaries are drained by the *umbilical* vein which returns to the embryo parallel to the umbilical artery (Fig. 250). The uterine wall, in the region of the chorionic villi, is also highly *vascularized;* and this tissue constitutes the maternal part of the *placenta*. The central part of the placenta has the form of a circular disc, embedded in the uterine wall at the site of implantation (Fig. 250); but some placental tissue tends to grow out and surround the foetus quite completely (Fig. 249).

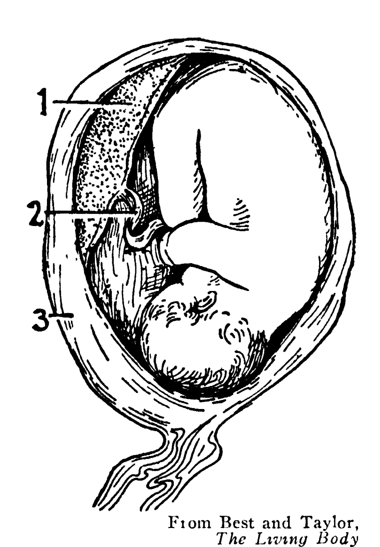
In the placenta the maternal and embryonic bloods do not intermingle, but they come into osmotic equilibrium with each other, because the two separate sets of capillaries lie very close



Courtesy of W. Chesterman, Oxford University

Fig. 249.—Human embryo (7.1 mm. long) enclosed in the embryonic membranes. The yolk sac lies below, connected with the embryo by the umbilical cord. The embryo almost completely fills the amniotic cavity, which is bounded by the plainly visible amniotic membrane. The outermost membrane is the chorion, from which the tufted chorionic villi (embryonic part of the placenta) protrude. Gill slits appear on the side of the neck, and the mesodermal somites show plainly along the dorsal margin of the trunk. The limbs are present, but no fingers or toes have yet been formed.

together over an extensive area. Oxygen and other food substances are transmitted by osmosis from the maternal to the embryonic blood—and this compensates for the fact that mammalian eggs contain a very small supply of yolk. Moreover, metabolic wastes, such as urea and carbon dioxide, pass by osmosis into the maternal blood and do not accumulate in the blood of the embryo.



From Best and Taylor, *The Living Body*

FIG. 250.—Usual position of the foetus shortly before birth. 1, placenta; 2, umbilical cord; 3, uterus.

At the end of the gestation period, *delivery* is initiated by the rupture of the embryonic membranes, in the region near the cervix. This first liberates the amniotic fluid; and shortly thereafter the foetus is forced through the vaginal passage by a rhythmic series of massive contractions of the uterine wall. After the umbilical cord is tied and cut, the infant must depend upon its own nutritive organs. The *after-birth*, which is delivered shortly after the foetus, represents a part or all of the placenta. In man and some other Mammals, the whole placenta, including the maternal part, is expelled, but in other Mammals, the maternal tissues of the placenta are retained within the womb.

All Mammals, except the *Monotremes* and *Marsupials*, are called *placentates*, due to a common possession of the placenta. The Monotremes are oviparous and display an essentially reptilian embryogeny. The Marsupials, which include the kangaroo, and other *pouched* Mammals, have a fairly well-developed uterus, but *no placenta*. Lacking adequate facilities for sustaining the foetus until development is complete, the Marsupials deliver their young "prematurely." When born the young Marsupial is deposited in a pouch—an infolding of the body

wall. This pouch also surrounds the mammary glands, so that the young are suckled and protected until a fuller development is reached.

As is shown by the fossil record, Monotremes and Marsupials were much more prevalent in an earlier evolutionary era; but a retrogression of the non-placentates occurred shortly after the placentates began to offer serious competition. However, in Australia, which was isolated from the mainland before the placentates became numerous, the non-placentates, especially the Marsupials, continue to prosper in considerable number and variety.

Asexual Multiplication in Multicellular Animals. Sexual reproduction is virtually universal among multicellular animals; but many species, especially among the invertebrates, also reproduce asexually—by methods that do not involve fertilization. These asexual processes include parthenogenesis—which was discussed previously (p. 324)—as well as *budding* and *fission*.

Fission and Budding. The direct splitting of an organism into two more or less *equal* parts is called *binary fission*. However, sometimes a new individual arises from a relatively small piece of the parent, and this asexual method of reproduction is called *budding*. Among multicellular forms the equal or unequal fragments which generate such new individuals consists of several or many cells.

Some Coelenterates, Flatworms, and Annelids regularly multiply by fission. Among the Flatworms the division is always transverse, forming two elongate pieces, which separate and regenerate the missing organs. In some worms, however, the separation is delayed, until several other fissions begin to cut across the serially arranged pieces (Fig. 251). Such a process of fission gives rise to a chainlike colony, which persists until the individuals separate. From an evolutionary viewpoint, this type of fission may be important, because it may provide a clue as to how *segmented* animals have arisen. In fact it is considered possible that the *segmented* type of body, which occurs in many higher animals, arose from a permanent association of such colonial individuals.

In some animals the young embryo undergoes fission, and this process of *polyembryony* gives rise to two or more embryos derived from a single egg. Certain parasitic "bees" and "wasps" produce hundreds of offspring from each egg; and one Mammal, the Nine-banded Armadillo, regularly produces four young, by two fissions of each early embryo. Likewise polyembryony sometimes occurs in man and other Mammals. In man, the result is usually *identical twins*—although multiple fissions, resulting in identical triplets, quadruplets and even quintuplets, have been recorded. These offspring bear a very close resemblance one

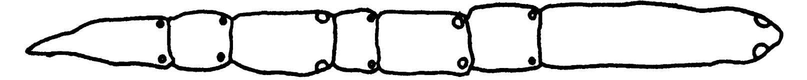
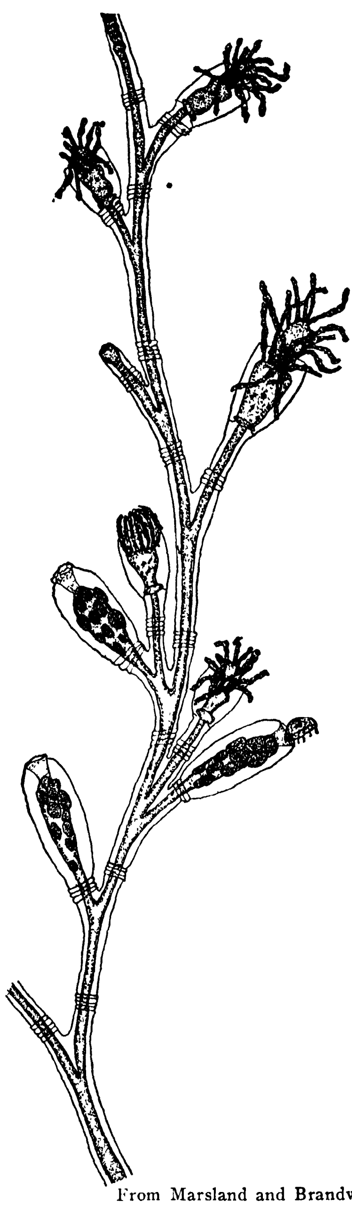


FIG. 251.—Colony formation due to fission, in a Flatworm (Stenostomum grande). The eye-spots of the members of the colony are shown as small circles. Semidiagrammatic. (After Child.)

to another, because they all arise from the same zygote, and all receive an identical set of genes and chromosomes. Ordinary *fraternal* twins, unlike identical twins, arise from separate zygotes; and consequently fraternal twins do not tend to resemble each other any more than other brothers and sisters. On rare occasions, in man and other Mammals, incomplete embryonic fission may occur, producing grossly abnormal offspring, such as "Siamese twins"; or individuals with a supernumerary head or limbs.

Budding, which occurs in some Flatworms and Annelids, and in many Sponges, Coelenterates and Tunicates, is well exemplified by the case of Hydra (Fig. 34). In Hydra the bud originates as a local accumulation of germ cells. These cells soon develop into a small but perfect offspring, which sooner or later becomes detached from the parent. In many other Coelenterates, however, the developing buds remain attached to the parent, forming colonies in which considerable differentiation occurs amongst the associated individuals (Fig. 252).

Regeneration. In many *primitive* animals such as Hydra, even a small piece of the body can regenerate into a whole ani-



From Marsland and Brandwein, *Manual of Biology*

FIG. 252.—Considerable structural and functional differentiation may occur between members of a colony—as is shown by Obelia and many other Coelenterates. The upper (four) members are nutritive zooids, which ingest and digest food for the colony as a whole; whereas the lower members are reproductive zooids, which are responsible for reproducing the species.

mal; and some lower forms fragment so readily that it is difficult to draw a sharp line between accidental regeneration and normal reproduction by multiple fission.

In higher animals, such as Molluscs, Arthropods and Vertebrates, the power of regeneration is more limited. Many of these animals can regenerate parts of the body, such as a limb that has been lost or injured; but the limb cannot regenerate a whole animal. Moreover, if the whole body be divided into two or more parts, all the parts will die. Among vertebrates, fish can regenerate fins and tails; and salamanders may regenerate tails, legs and jaws. An adult frog cannot restore a lost leg, but a tadpole can. Adult reptiles, birds and Mammals cannot replace lost limbs, although lizards (but not other reptiles) can regenerate the tail. In Mammals, the regeneration of external parts is limited to the growth of skin and connective tissue over wounds; but some of the internal organs—especially the liver and some other glands—have considerable powers of regeneration.

TEST QUESTIONS

1. Provide an example in each case:
   a. temporary gonads;
   b. a monoecious animal;
   c. external fertilization;
   d. mutual insemination.
2. Some animals produce many eggs, others very few. Explain.
3. Identify, locate, and give the connections of: (a) seminiferous tubules; (b) interstitial tissue; (c) inguinal canal; (d) epididymis; (e) vas deferens; (f) urethra.
4. Make a labelled diagram to show all the parts and connections of the human male reproductive tract.
5. Discuss the functions of the seminal vesicles, the prostate, and the glands of Cowper.
6. Make a labelled diagram to show the parts and connections of the human female reproductive tract. Specify the function or functions of each part.
7. Distinguish between amplexus and copulation.
8. Identify, locate, and state the functions of:

a. the Graafian follicles;
b. the corpus luteum;
c. the ostium.

9. Identify and describe in terms of the human species: (a) ovulation; (b) fertilization; (c) implantation; (d) the decidual reaction; (e) the growth of the foetus; (f) delivery.
10. Distinguish between ovipary and vivipary. Which is more prevalent among vertebrates? Explain.
11. How does the amnion differ from the allantois as to its origin in the embryo?
12. What is the amniotic fluid and why is it important?
13. Explain the functional importance of the allantois: (a) in reptiles and birds; (b) in Mammals.
14. What is the placenta?
15. How is the placenta related to:
    a. the chorionic layer of the amniotic fold;
    b. the allantois;
    c. the tissues of the uterus?
16. What are the chorionic villi and why are they important?
17. Adrenalin injected into the maternal blood stream accelerates the heart beat of the foetus as well as of the mother. Explain.
18. Trace a sample of blood from the umbilical artery to the umbilical vein (Fig. 245).
19. For each of the following substances, state whether it tends to pass (a) from the maternal to the embryonic blood, or (b) from the embryonic to the maternal blood, in the capillary system of the placenta: (1) glucose; (2) CO_2; (3) urea; (4) O_2.
20. What is the after-birth? How does it differ in different Mammals?
21. Specify two kinds of non-placentate Mammals. Explain why such creatures found difficulty in competing with the modern Mammals.
22. Distinguish between:
    a. budding and fission;
    b. identical and fraternal twins;
    c. complete and incomplete embryonic fission.
23. Discuss the possible relation between fission and segmentation.

FURTHER READINGS

1. *Ourselves Unborn*, by George W. Corner; New Haven, 1944.
2. *Atlas of Human Anatomy*, by Frohse, Broedel and Schlossberg; New York, 1942.
3. *The Living Body*, by C. H. Best and N. B. Taylor; New York, 1944.

CHAPTER 21

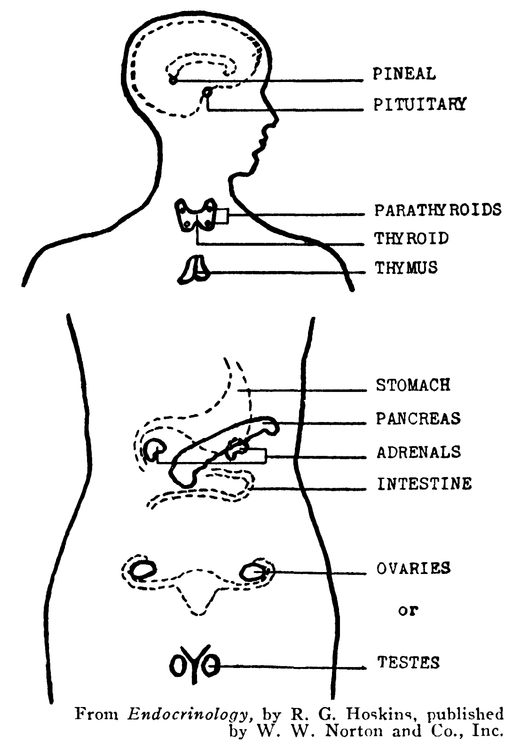
THE ENDOCRINE GLANDS

THE MANIFOLD functions of the body are integrated partly by the *nervous system*, and partly by the *endocrine glands*. Each endocrine gland secretes one or more highly active organic compounds directly into the blood stream, and these *hormones* control activity in many parts of the body. Compared to the rapidly executed effects of the nervous system, hormonal control is more deliberate and sustained. Consequently the endocrine glands are especially important in determining the slower and more enduring adjustments by which each organ keeps pace with the changing activities of the other body parts.

The Endocrine Glands. All the glands of the endocrine system are shown diagrammatically in Fig. 253. Some of these glands—i.e., the *thyroids*, *parathyroids*, *pituitary* and *adrenals* —are purely endocrine in function, and these glands *possess no ducts*. Such ductless glands send *all* of their secretions into the blood stream; or in other words, the ductless glands secrete *internally*, into the blood, rather than externally, into a duct. However, the endocrine system also includes such duct-possessing glands as the *pancreas*, *ovaries*, and *testes*, which secrete both internally and externally; and there are some organs, like the stomach and intestine, which produce hormones as a minor, or incidental sideline to their regular activity (p. 377).

Methods of Endocrine Research. *Deficiency* and *replacement* experiments are widely used in endocrinology. If a gland is removed from an animal, and the animal develops drastic dysfunctions as a result of the deficiency, there is no justifica-

tion for believing that the excised organ is an endocrine gland —unless the impaired functions can be restored by replacing the gland, i.e., grafting it in another part of the body, or by injecting extracts prepared from the excised tissue. Replacement



From *Endocrinology*, by R. G. Hoskins, published by W. W. Norton and Co., Inc.

FIG. 253.—Location of the endocrine organs in the human body.

by glandular extracts is a particularly valuable technique, because the method of extraction provides a good index of the chemical nature of the hormone. Moreover, if more than one hormone is present in the excised gland, these hormones can be separated by preparing different extracts. In this way, for example, several distinct hormones have been obtained from the pituitary gland; and each separate hormone restores some but not all of the dysfunctions associated with the removal of the whole pituitary gland.

Overdosage methods are also quite useful in endocrinology. Grafting extra gland tissue, or injecting extracts—without first removing the gland in question—may give symptoms opposite to the deficiency effects; or in clinical cases, *hyperactivity* of a diseased gland may provide some clue as to the normal functions.

In the final analysis, however, a hormone is not established until it has been *isolated* and *identified* as a pure substance. In recent years this goal has been reached in the case of a number of hormones (see later); and some of these compounds have been *artificially synthesized.*

The Testis as an Endocrine Gland. In addition to its sperm-forming function, the testis produces *testosterone,* a very active hormone which stimulates the development of the *secondary sexual characteristics* of *maleness* in all vertebrate species.

The drastic results of *castration,* over and above the mere development of sterility, have been recognized since ancient times; and several classical accounts describe the characteristics of the *eunuch,* especially emphasizing the high-pitched voice, the hairless face, obesity and mental inertia. In fact several ancient peoples resorted to castration, employing the eunuchs as keepers of the harem.

The castration of any vertebrate tends to suppress the *secondary sexual characteristics* of the species. The *capon,* for example, lacks the large comb of the *cock,* and the body of a capon becomes unusually plump. The *gelding* also becomes heavier and more docile than the *stallion,* and hence the gelding is more useful as a beast of burden.

The secondary characteristics of the male can be restored to the castrate, either by grafting or injecting testicular material; and this fact provided the first evidence that the testis is an endocrine gland. In the capon, for example, the characteristics of the cock—aside from fertility—can be restored by a suitable regime of testicular injections; and, in fact, even a young *hen* will take on the bodily features and habits of a rooster, if subjected to a similar treatment.

Testosterone is produced by the *interstitial tissue* of the testis, which occupies the space between the sperm-forming tubules (p. 493). This fact was first discovered from clinical evidence. In cases of cryptorchy (p. 493), the *undescended testis* displays a normal amount of interstitial tissue, but the sperm-forming tubules are degenerate. Thus a bilateral cryptorch, although completely sterile, lacks none of the secondary attributes of masculinity. The temperature in the abdominal cavity is higher than in the exposed scrotal sac, and such a temperature damages the sperm-forming tissues, but does not harm interstitial cells. Thus if a testis is transplanted from the scrotum into the body cavity, the interstitial tissues persist, but the tubules degenerate. Moreover the importance of the interstitial tissue is borne out by X-ray experiments. A suitable dosage of X-radiation virtually destroys the tubules of the testis, without impairing the interstitial cells. Subsequently the treated individual is sterile, but still he retains the secondary characteristics of the male.

Isolation of Testosterone. In 1932, *testosterone*, $C_{19}H_{30}O_2$, was isolated from a massive extract of sheep testes; and this steroid compound is generally acknowledged to be the main testicular hormone. This crystalline compound is so potent that just one hundredth of a milligram (.00001 gm.) will produce a measurable enlargement of the comb of a capon; or in other words, one gram—the quantity extractable from about a ton of fresh testes—will give an appreciable effect in 100,000 birds.

In addition to testosterone, several other steroid compounds, having a distinctly similar though usually less potent action, have been identified. Some of these *androgenic compounds* are probably metabolic derivatives or precursors of testosterone, since they can be extracted from many tissues and from the urine. Others, however, are purely synthetic products which derive their androgenic potency from the similarity of their chemical structure to the natural androgens.

Puberty. Except for the primary difference in the sex organs proper, there is scarcely any sex differentiation in newborn children; and this lack of differentiation between the sexes

persists until the time of puberty. At puberty, however, the interstitial tissues of the testes become active, and soon the newly mobilized testosterone begins to take effect. Now the boy becomes broader-shouldered and more muscular; the voice deepens and the beard begins to grow; also there is a growth of hair in the axillary and pubic regions; and finally the genitalia proper take on the proportions of an adult.

The Ovary as an Endocrine Organ. In the female, the counterpart to testosterone is played by an ovarian hormone, estrogen, which is produced by the Graafian follicles (p. 498). These follicles lie dormant in the ovary until the time of puberty and then they ripen and begin to secrete estrogen.[1]

The puberty changes of the female body are initiated by the liberation of estrogen from the newly developing follicles. Gradually the body contours lose their angularity, and the pelvis becomes somewhat broader; the breasts begin to develop, and there is an appreciable growth of the uterus and the vagina. But the complete development of the reproductive structures, and the establishment of a menstrual cycle, necessitates the intervention of a *second* ovarian hormone. This is the hormone, *progesterone*, which is produced by the *corpus luteum.*

Isolation of the *ovarian hormones* entailed the cooperation of biochemists and physiologists in several nations; and all the ovarian hormones prove to be steroid compounds, similar in structure to testosterone.

The Ovarian Hormones and the Estrus Cycle. Among most Mammals, the female of the species displays a distinct and periodic rhythm of sexual activity; and this so-called *estrous cycle* is dominated by the ovarian hormones. A dog or cat, for example, comes into "heat," or *estrus*, only about twice yearly; but such species as rats and mice have the cycle which recurs much more frequently. Usually the female is receptive to the male only at the time of estrus; and regularly the Graafian follicles reach maturity and *ovulation occurs* at a definite time in the estrus period.

[1] *Estrogen:* the one or more hormones produced by the follicles.

The Menstrual Cycle. In man and the anthropoid apes, the period of estrus is not distinct; and the situation is complicated by the occurrence of *menstruation.* However, the menstrual cycle is likewise dominated partly by the follicular hormone, estrogen, and partly by the luteal hormone, progesterone.

The average menstrual cycle endures for a total period of twenty-eight days during which only one Graafian follicle usually ripens and ovulates. Starting at the time when the menstrual flow has just abated, a new follicle commences to develop. This new follicle reaches maturity usually on the 12-18th day, and this is the time when ovulation normally occurs (Fig. 254).

The follicle continues to increase its production of estrogen as it matures, passing the increased amounts of the hormone into the blood stream, from the accumulating follicular fluid, until the follicle ruptures and liberates the egg.

In addition to stimulating the growth of the mammary glands, uterus and vagina at the time of puberty, estrogen exerts a cyclic (monthly) influence upon the growth of the mucosal lining of the uterus. Each month as a result of menstruation the uterine mucosa is virtually destroyed; and in fact, the menstrual discharge consists of mucosal debris, together with some blood which escapes from the subjacent capillaries in the uterine wall. Thus an important function of estrogen is to stimulate the initial stages of regeneration and reconstruction in the internal lining *immediately after menstruation.* However, estrogen alone is inadequate to complete the reconstruction of the uterine mucosa: without the subsequent action of progesterone, an implantation of the embryo cannot occur, and pregnancy cannot take place.

Following ovulation (Fig. 254), the *corpus luteum* develops, usurping the region formerly occupied by the follicle; and from about the 15th to the 26th day of the menstrual cycle, the luteal hormone, *progesterone,* is produced in increasing amounts.

Progesterone exerts a very important influence upon the structure and activity of the female reproductive organs: (a) it inhibits the ripening of new Graafian follicles, and consequently further ovulations do not occur while the corpus luteum is ac-

tive; (b) it stimulates a continued growth of the uterus, and perfects the reconstruction of the uterine mucosa, which now becomes highly vascular and capable of effecting an implantation of the embryo; (c) it inhibits muscular contractions in the uterine wall; and (d) it augments the growth of the mammary glands.

Obviously all these effects of progesterone are preparations for the event of pregnancy; and in fact, if pregnancy does occur, the corpus luteum persists until the gestational period is almost

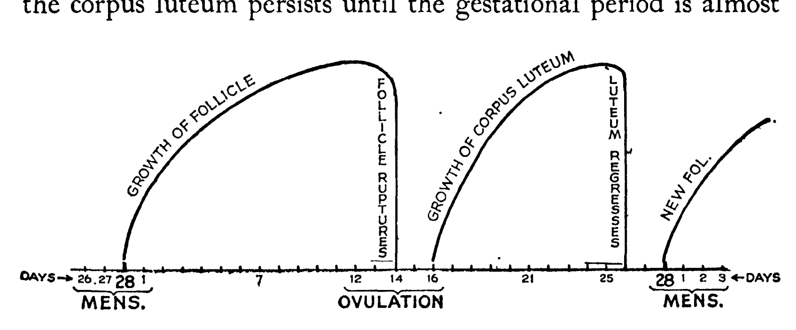


FIG. 254.—The menstrual cycle in relation to the ovarian hormones.

completed. However, if the egg is not fertilized, the corpus luteum suddenly retrogresses—on the 25-27th day of the menstrual cycle. This sudden withdrawal of progesterone precipitates a breakdown of the uterine muscoa, and leads to the menstrual flow. Moreover, when the corpus luteum subsides, another Graafian follicle—freed from the inhibiting effects of progesterone—begins to ripen; and this marks the beginning of the next menstrual cycle (Fig. 254).

The human ovum, subsequent to the time of ovulation, remains fertile for a very limited time. Ordinarily the egg can be fertilized only while it is passing through the Fallopian tube —a matter of about 24 hours. Likewise, sperm remain viable in the female reproductive tract for only about 2 days. In view of these factors the period of maximum fertility is closely associated with the time of ovulation, which *usually* occurs from the 12-18th day of the cycle. However, extremely early and extremely late ovulations are known to occur in some cases.

Progesterone as a Factor in Pregnancy. Without progesterone, the decidual reaction cannot be elicited from the uterine mucosa, and consequently an implantation of the embryo cannot occur. Normally, however, the corpus luteum is well developed at the time when the embryo descends into the uterus; and at this time the uterine wall is so receptive that it can be induced to envelop almost any small object, however inert and foreign it may be.

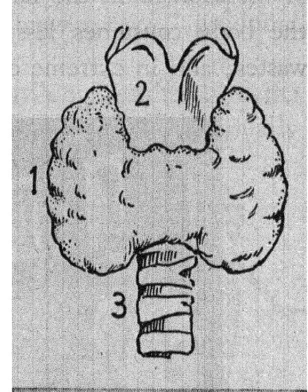
If the corpus luteum is destroyed very early in pregnancy, the uterine mucosa retrogresses and *abortion* follows. But in a normal pregnancy the corpus luteum persists and the placenta produces progesterone and gonadotropic hormones (p. 536). Accordingly, the uterus continues to enlarge; the uterine contractions are held in check; the mucosa is maintained; and the mammary glands continue to develop. Then near the end of the pregnancy, the corpus luteum involutes, and the placenta becomes less active. Deprived of progesterone, the uterine mucosa retrogresses and loses its capacity to nurture the foetus. Then the musculature of the womb becomes active, and the foetus is forcibly delivered through the dilated vaginal canal.

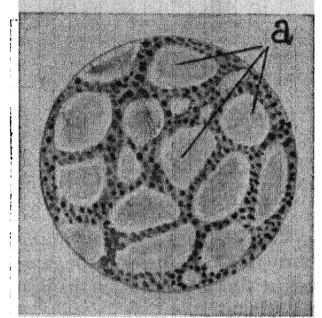
Hormonal Control of Lactation. All Mammals suckle their young with milk from the mammary glands. The breasts undergo an initial development at the time of puberty; and further development occurs during pregnancy. However, it is only after *parturition* (delivery of the foetus) that the mammary glands are capable of producing milk.

At least three hormones, namely estrogen, progesterone, and *lactogen* (p. 536), must act successively in preparing the mammary glands for secretion. At puberty, estrogen produces an initial growth of the glands, but this growth soon reaches a maximum. During the menstrual cycle there is a slight waxing and waning of the mammary tissue, following the rise and fall of progesterone; but during pregnancy progesterone has time to produce a much larger effect. However, the actual production of milk can only be elicited after parturition, when the pituitary gland begins to liberate significant quantities of lactogenic hormone.

The rudimentary mammary glands of a male dog, or other laboratory animal, are sometimes used to test the potency of the lactation hormones. By suitably timed injections of estrogen, progesterone, and lactogen—each used successively—the mammary glands of the male can be developed quite completely, and milk can be obtained.

The Thyroid Gland. The human thyroid is a small bi-lobed gland which lies in the neck, along the sides of the trachea. The two lobes are connected by the *isthmus*, a narrow strand of tissue which passes across the front of the trachea, just below the larynx (Fig. 255). The entire thyroid weighs only about an ounce; and the gland is purely endocrine in function.





From Best and Taylor, *The Living Body*

FIG. 255.—Upper drawing, 1, thyroid gland; 2, thyroid cartilage; 3, trachea. Lower, microscopic appearance of the gland; a, alveoli containing colloid.

The thyroid arises in all vertebrate embryos, as an outgrowth from the floor of the pharynx. All vertebrates also possess *parathyroid* glands, which arise from the wall of the pharynx. In many species the parathyroids lie some distance from the thyroid; but in man the parathyroids are four small bean-shaped bodies, imbedded in the thyroid tissue. This fact led to considerable confusion, because early investigators sometimes removed the parathyroids inadvertently when they were excising the thyroids.

The importance of the thyroid was suspected even in ancient times; but in 1885 replacement experiments gave definite proof of a thyroid hormone; and in 1916 *thyroxin* ($C_{15}H_{11}O_4NI_4$) was isolated for the first time. Thyroxin successfully counteracts

the effects of thyroidectomy, although the hormone appears to be carried in the blood stream as a thyroxin-protein compound.

The *primary* effect of the thyroid hormone is upon the rate of *metabolism* in the body tissues. With inadequate thyroxin, the body consumes less oxygen and produces less metabolic wastes; and in extreme cases the *basal metabolism* falls to less



From Best and Taylor, *The Living Body*

FIG. 256.—Thyroidectomized cretin lamb about fourteen months old and a normal sheep of the same age. The thyroids had been removed from the cretin about twelve months previously. (After Sutherland Simpson.)

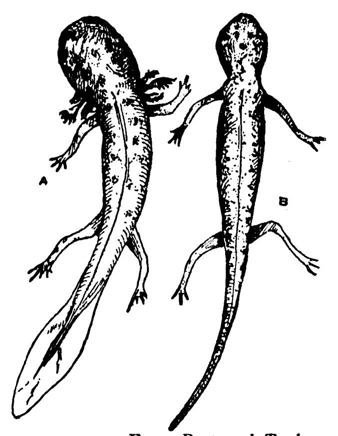
than 30 per cent of normal. Conversely, an excess of thyroxin elevates the metabolic rate considerably above normal levels.

Many of the severe symptoms which accompany thyroid derangement probably represent secondary effects, resulting from the drastic metabolic changes in the various organs. Also the net results are different depending upon whether the thyroid deficiency (or excess) is experienced before or after the animal reaches maturity.

Hypothyroidism in young animals retards development very profoundly (Fig. 256). In tadpoles, for example, metamorphosis into adult frogs does not occur if the thyroid is destroyed at an early stage. This situation has a parallel in the *Axolotl*, a kind of salamander which inhabits the highlands of Mexico.

This species possesses a hereditary defect of the thyroid and does not develop beyond the gill-bearing "tadpole stage." However, if thyroxin is administered, the Axolotl completes development like other salamanders. Soon it loses its gills and becomes a true land animal—a sort of "new species," produced artificially (Fig. 257).

Overdosage experiments also give striking results as to the role of the thyroid in development. If tadpoles are continually fed with minced sheep thyroid, they develop with astonishing rapidity. In fact, such a tadpole becomes a full-fledged frog long before it has a chance to grow to a suitable size; and in some experiments these miniature adults were scarcely larger than houseflies.



From Best and Taylor, *The Living Body*

FIG. 257.—Axolotls. (A) has not been treated. (B) has received thyroid extract. Note the disappearance of the gills and fin.

In a new-born child a seriously *underactive* thyroid leads to *cretinism*. This condition is now quite rare—but formerly cretins were often encountered in the Alps and certain other districts where the iodine content of the soil—and consequently of the local produce—is exceptionally low. Lacking iodine, the thyroid is unable to synthesize thyroxin; and then gradually the thyroid tissues lose their normal structural characteristics. Typically the cretinous child is very small and malformed, with swollen tongue and puffy skin; and physical and mental development are scarcely perceptible even after years. The disease gives a very dramatic response to thyroxin, however, if the hormone is given in the early stages.

In adults the commonest forms of *hypothyroidism* are *myxedema* and *endemic goiter*. Both of these conditions may arise from inadequate iodine in the diet; although probably there are other contributing factors, including hereditary abnormalities.

In myxedema the thyroid deficiency is relatively great, but there is no appreciable swelling of the thyroid tissue—which, in fact, may become degenerate. Usually the myxedematous patient displays a basal metabolism which is 25 per cent below normal. The subject complains of cold, and, indeed, with the metabolism at so low an ebb, the body temperature may fall as much as 4 degrees. Extreme physical and mental lethargy are common, and sometimes there is a tendency toward obesity. Also the skin becomes puffy and doughy, due to a deposit mucoid material in the deeper layers. In some cases, myxedema responds to the addition of iodine to the diet; but more generally it is necessary to give the thyroid hormone.

In *endemic goiter* the deficiency is relatively mild, so that the fall in basal metabolism is usually not more than 15-20 per cent. A swelling of the thyroid tissue forms the goiter, which usually protrudes from the neck. The swelling is due to the accumulation of a colloid fluid in the thyroid tissue, and consequently this type of goiter is also called *colloid goiter.*

Typically endemic goiter results from a deficiency of iodine, and the swelling may represent an attempt by the gland to compensate for the lack of iodine. Endemic goiter tends to be localized in certain regions. Detroit, for example, occupies a locality where the soil lacks iodine; and in 1924, 36 per cent of the school children of this city displayed endemic goiter—at least in the incipient stages. Seven years later, however, subsequent to the compulsory addition of small quantities of potassium iodide (KI) to the table salt of the region, the incidence of goiter in the school population of Detroit had dropped to less than 3 per cent.

A swelling of the thyroid does not invariably indicate that the gland is underactive. In fact the commonest form of *hyperthyroidism* is found in *exophthalmic goiter*, or *Graves' disease.* In this condition the swelling is apt to be moderate, although the degree of hyperactivity may be very great.

The basal metabolism of a hyperthyroid patient may be more than doubled, and such an acceleration of the metabolism of the tissues has drastic consequences. The nervous and mus-

cular systems become hyperirritable; and there is profuse sweating, insomnia and muscular tremors. The subject eats more food, yet loses weight. The blood pressure rises and the heart may be overworked to a serious degree. Moreover this type of goiter is usually marked by a protrusion of the eyeballs (exophthalmos), although the underlying cause of this peculiar symptom probably lies in the pituitary gland, rather than in the thyroid. In fact the factor which induces the goiter and drives the gland to such extremes of activity seems to be an overproduction of the thyrotrophic hormone (p. 536) by the pituitary gland. To alleviate the condition, however, the surgeon usually removes a certain proportion of the thyroid, guiding his judgment by preliminary measurements of the metabolic rate. Also X-rays and radium may be used to destroy some of the thyroid tissue; and recently certain drugs which inhibit the synthesis of the thyroid hormone have given promising results.

The Parathyroid Glands. A hormone has not been isolated from the parathyroids, although there are many indications that the parathyroid hormone represents one or more specific protein compounds.

The parathyroids are completely essential to life; and without replacement therapy, the animal dies in about 3 weeks after the parathyroids are removed. This result is amply substantiated in a variety of species, including man; and in surgical history there are records of several cases in which the parathyroids were sacrificed inadvertently, during operations on the thyroid (see Fig. 253).

Usually within 2-3 days after the removal of *all* the parathyroid tissue, an animal displays severe muscular tremulations and then violent cramps and convulsions. Such a condition of *tetany* gradually progresses to the point of exhaustion, and the victim dies in a comatose state. Rarely, the tetanic phase of the disorder does not appear, in which case there are only muscular weakness and a slow wasting of the tissues.

The parathyroids appear to have a critical effect upon the metabolism of calcium and phosphorus in the tissues. Following

the removal of the glands, the blood calcium level falls, and the severity of the symptoms runs parallel, at least roughly, to the degree of calcium depletion. Moreover, the symptoms of parathyroid insufficiency are held in abeyance quite indefinitely, by injections either of parathyroid concentrates, or of calcium solutions—although best results are obtained when both are used. With overdoses of parathyroid concentrates, the level of calcium in the blood becomes too high, but the blood content of phosphorus tends to fall away. Also there is a marked depletion of both calcium and phosphorus compound in the tissues, especially in the bones.

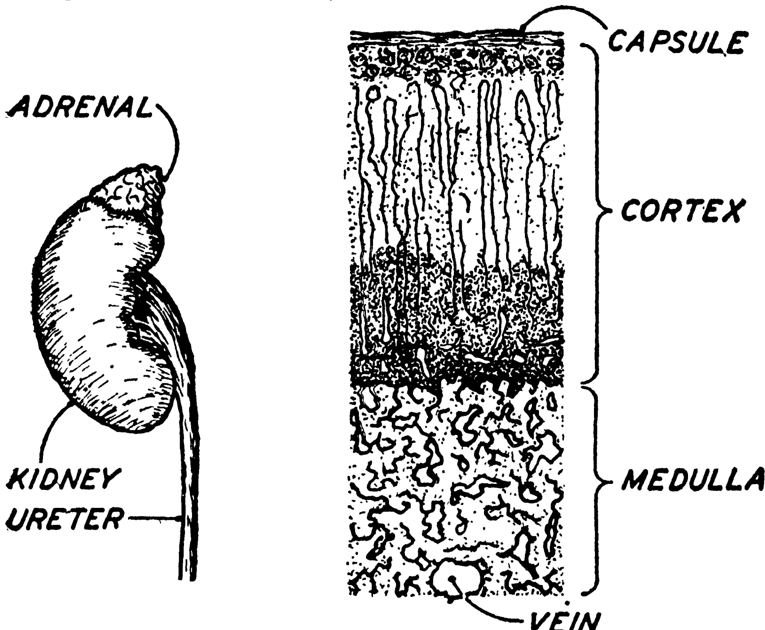
The Adrenal Glands. In man, each adrenal gland perches like a small cap on the upper end of the corresponding kidney (Fig. 258). Both glands together weigh less than one ounce, but the adrenal blood supply is very copious.

Each adrenal is a duplex gland which in section displays a dark-brown central core, the *medulla*, surrounded by a paler shell of tissue, the *cortex* (Fig. 258). These two distinct parts of the adrenal arise separately in the embryo: the cortex from the mesodermal lining of the coelom; and the medulla from an ectodermal outgrowth of the neural tube. Likewise the cortex and medulla have distinctly different functions in the adult body; and, in fact, an animal survives quite well without any adrenal medulla, but cannot live in the absence of all cortical tissue.

The Adrenal Medulla. *Adrenalin* ($C_9H_{13}O_3N$) was isolated quite early (1904), and probably this hormone is the only endocrine product of the medulla. Adrenalin (which is also called epinephrine and adrenin) has been synthesized artificially; and chemists have likewise produced several other drugs, such as *ephedrin*, which exert a comparable action in the body.

The physiological effects of an adrenalin injection are widespread and potent. The heart action becomes stronger and quicker; but the digestive tract becomes quiescent. The skin pales, the pupils dilate, and the hair erects. Moreover, adrenalin produces a marked effect upon the arteries. The arteries supply-

ing the viscera and skin become constricted—which shunts most of the circulation into the lungs, muscles, and brain. The spleen contracts, augmenting the total quantity of circulating blood; and the liver draws upon its glycogen reserves to mobilize additional blood sugar. Also the coagulation reactions of the blood are speeded up considerably.



From Carlson and Johnson, *The Machinery of the Body*, by permission of the University of Chicago Press

FIG. 258.—The adrenal gland, showing its location (in man), capping the upper pole of the kidney. The microscopic section (right) shows the division into cortex and medulla. The section is not magnified enough to show individual cells.

In sum total, adrenalin simulates a generalized excitation of the whole *sympathetic* nervous system (p. 602). The body displays a similar picture under stress of fear and anger, which likewise call forth a widespread hyperactivity of the sympathetic nerves. These observations form a basis for the *emergency theory of adrenal function.* According to this view, the sudden release of extra adrenalin in times of stress is instrumental in transforming the body into a more effective "fighting machine."

The Adrenal Cortex. An absence of the cortex accounts for the prostration and early death which follows a total extirpation of the adrenal glands; and adrenalectomized animals remain alive and free of drastic symptoms, if about 1/5 of the cortical tissue remains intact—irrespective of the presence or absence of any medullary tissue.

The symptoms of adrenal cortical insufficiency, which culminate in death, are numerous and obscure. Apparently there is a generalized derangement of carbohydrate metabolism. The tissues display an impaired capacity for deriving glucose from protein sources, and the blood glucose is apt to fall to a dangerous level. The osmotic characteristics of the blood are also seriously altered, due to a loss of inorganic salts, especially NaCl. Under these circumstances the blood plasma fails to maintain its normal volume, and the blood pressure falls drastically. During a protracted cortical insufficiency, the sex functions also fail. In males the seminiferous tubules degenerate; and in females, the Graafian follicles stop developing—or if pregnancy has started, abortion follows. Moreover, mothers with recently delivered offspring fail in the secretion of milk.

The first life-sustaining extract of the adrenal cortex, obtained in 1930, was named *cortin*. Subsequently many efforts have been made to isolate, purify and identify the individual active components of the extract; and these efforts have been partially successful. In fact, some twenty compounds have been obtained, among which *desoxycorticosterone* ($C_{18}H_{22}O_3$) is the most potent. All the isolated substances are steroid compounds, and all bear a close chemical relationship to the hormones produced by the testes and ovaries. Probably some of these compounds are merely derivatives of the one or more hormones naturally present in the intact cortex.

There are still a number of unsolved problems as to the functions of the adrenal cortex. The total potency of cortin (the unfractionated extract of the tissue) greatly exceeds the combined potencies of all the individual substances which have been isolated from the extract. Also the whole cortin extract, prepared

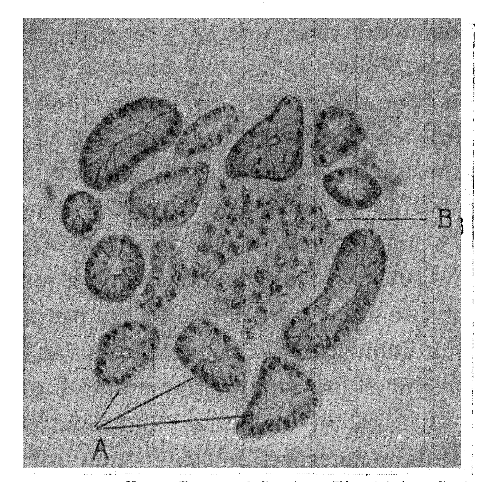
according to the best known methods, shows very little influence upon the sexual functions of the animal.

In man, the commonest type of adrenal cortex insufficiency is encountered in Addison's disease, a tubercular infection localized *mainly* in the cortex portion of the gland. A hyperactivity of the cortex is encountered in some cases of adrenal tumor. Such tumors, although very rare, especially in males, are apt to give rise to a condition known as *adrenal virilism,* which can appear at any age. In boys the sex organs, *except for the testes,* may approximate full size and maturity, at an age of 1 or 2 years; and simultaneously the hair, voice and body musculature take on the characteristics of an adult man. But even greater is the misfortune of a girl or woman who develops adrenal virilism. In this case, the bodily development is all in a masculine direction, producing a bearded face, deepened voice, and considerable muscularity. Simultaneously the ovaries, uterus and vagina begin to atrophy; but the clitoris enlarges, assuming the proportion of a penis. Such changes, in both male and female subjects, are somewhat difficult to interpret, although they may be due to a great overproduction of cortical hormones, some of which have distinct androgenic properties. All in all, therefore, many more data are needed before the problem of adrenal virilism can be clarified and brought under control.

The Endocrine Function of the Pancreas. An endocrine function of the pancreas was first suspected in 1892, when it was observed that depancreatized dogs quickly develop severe symptoms of a fairly common human ailment, *diabetes mellitus.* However, no hormonal activity could be found in the pancreas, until 1922. Then an extract capable of alleviating diabetes was prepared from pancreatic tissue; and in 1927, purified crystalline *insulin* was finally isolated. Insulin proved to be a protein compound which is digested by the *trypsin* of the pancreas; and unless precautions are taken to inactivate the enzyme before extracting the hormone, insulin cannot be obtained from the pancreatic tissues.

The main part of the pancreas consists of the digestive tubules

which form the pancreatic juice; but there are considerable masses of endocrine tissue occupying the spaces between the tubules (Fig. 259). This tissue makes up the *islands of Langerhans*, which secrete insulin directly into the blood stream. In the embryo, the endocrine tissue of the pancreas buds off from



From Best and Taylor, *The Living Body*

FIG. 259.—Section of pancreas. A, alveolar cells which secrete pancreatic juice. B, islands of Langerhans, responsible for insulin production.

the digestive tubules and loses all connection with the duct system of the gland.

Hypoinsulinism. Diabetes mellitus is a severe and fairly prevalent malady which has been recognized since antiquity. Without treatment, the diabetic displays great thirst, excessive urination, a steady and unchecked loss of weight, weakness, prostration, coma and finally death. Clinically the picture includes a very high blood sugar level; persistent glucose in the urine (sometimes approaching 8 per cent); depletion of the glycogen stores of the liver; and—when the comatose stage is reached—a distinct acidosis, with detectable amounts of acetone and related compounds in the blood and urine.

All these symptoms point to a generalized impairment of carbohydrate metabolism in the body. In the absence of insulin the tissues of the body seem to lose their capacity to oxidize glucose

effectively; and the liver fails to store glycogen adequately. Accordingly, glucose accumulates in the blood and drains forth in the urine. Even if carbohydrates are withheld from a diabetic, glucose continues to be formed and excreted. Despite the fact that the tissues cannot use it, glucose continues to be mobilized by an excessive deamination of absorbed amino acids; and even the tissue proteins are sacrificed to the same quite useless end. Also fats are oxidized to an excessive degree; and this leads to a piling up of incompletely oxidized fatty acids at the terminal stages of acidosis.

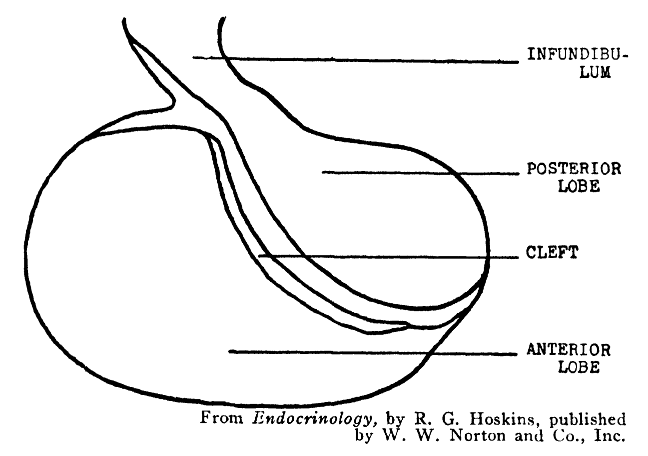
Injection of insulin alleviates the diabetic symptoms; but the action only persists for several hours. Consequently diabetics require a daily regime of insulin injections; and the maintenance of health depends upon a methodical adherence to the treatment—although rarely the endocrine tissues of the pancreas recover their normal function.

Hyperinsulinism. Unless accurately calibrated, an injection of insulin may overshoot its mark. In this case the blood sugar level sinks drastically and hypoglycemic shock ensues. Therefore, most patients take precaution to have sweet drinks on hand —to be taken at first sign of "post-injection shakiness." If shock ensues and the individual becomes unconscious, the attending physician may have difficulty in deciding quickly whether to give sugar for shock or insulin for diabetic coma.

The Pituitary. The *hypophysis*, or pituitary gland, is scarcely larger than a pea; and yet this gland is one of the most important in the whole endocrine system. The pituitary lies approximately at the center of the head, attached to the base of the brain by a stalk, the *infundibulum* (Fig. 260). Moreover, the pituitary is a double gland, consisting of two main parts: the *anterior lobe* and *posterior lobe*. The anterior lobe arises in the embryo as a pouchlike up-growth from the roof of the pharynx; whereas the posterior lobe is a solid down-growth from the floor of the brain. These parts of the embryonic pituitary make contact; but the anterior lobe grows more rapidly, partially encompassing the posterior lobe. In the adult, all connec-

tion between the anterior lobe and the oral cavity is lost—except in rare anomalous cases; but the connection of the posterior lobe with the brain persists as the infundibulum.

Pituitary research has been very active for many years; but it still presents a number of unsolved problems. The work is very difficult, because the gland lies in a relatively inaccessible



From *Endocrinology*, by R. G. Hoskins, published by W. W. Norton and Co., Inc.

FIG. 260.—The pituitary gland of man.

position, and because most, if not all, of the pituitary hormones are protein compounds, which are difficult to isolate and identify.

Deficiency and Overdosage Experiments. Rats are excellent specimens for pituitary research, because the pituitary of the rat is relatively easy to remove by operating through the roof of the mouth. When this operation is successful, no damage is done to the overlying brain; and there is seldom any infection even in the absence of aseptic precautions.

Deprived of the pituitary, the animal displays a number of characteristic symptoms. Young specimens stop growing and never reach sexual maturity. In adults, the males suffer a distinct retrogression of the testes and accessory reproduction structures; and females display a degeneration of the ovaries, uterus, and vagina. Also both sexes are prone to show an atrophy of the adrenal cortex and of the thyroid glands.

Consistent results are also obtained by overdosage with pitu-

itary material, either in the form of injected extracts, or from the implantation of extra glands. Characteristically young animals grow prodigiously, reaching a state of gigantism—with a very early onset of sexual maturity. Also adult specimens display hypertrophy and hyperactivity of the primary and secondary sex organs, as well as of the thyroid and adrenal cortex.

Hormones of the Anterior Pituitary. On the basis of these and many other experiments, several separate anterior lobe hormones are now postulated. These include *somatotrophin*, which is better known as the *growth hormone;* the *gonadotrophins*, a group of hormones which act primarily on the sex organs; and also *thyrotrophin*, *corticotrophin* and *mammotrophin*, which act respectively on the thyroid, adrenal (cortex), and mammary glands. Other anterior pituitary hormones are also indicated; but these will be excluded from the present account.

The Growth Hormone. Human cases of *gigantism*, with statures greater than 9 feet, were recorded by the Greeks and Romans, but it was not until about 1860 that the condition was related to an overactive pituitary. More recently, the work of separating the growth-promoting substance from crude pituitary extracts finally culminated in 1944 with the isolation of a pure protein, *somatotrophin.* This hormone is exceedingly potent in restoring growth to hypophysectomized animals.

The *pituitary giant* is a well-proportioned individual, although the overgrowth of the limbs exceeds that of the other body parts. Likewise the *pituitary midget* may be quite normal, except for extremely diminutive legs and arms. Apparently hyperactivity or hypoactivity of the pituitary *may* be restricted largely to the tissue that secretes the growth hormone.

Acromegaly is another human ailment in which an excess of somatotrophin appears to be the major factor. In acromegaly the hyperactivity of the pituitary is usually due to a tumorous condition, which develops after an individual reaches maturity. By this time the capacity for skeletal growth is largely restricted to the hands, feet and facial regions; and if acromegaly persists, the jaws become abnormally long and broad, and the brows en-

large to beetling proportions. Also the bones of the hands and feet become abnormally thickened, especially at the joints of the fingers and toes.

The Gonadotropic Hormones. At least two gonad-stimulating fractions have now been separated. These are called FSH (follicle-stimulating hormone) and LH (luteinizing hormone). Both of these compounds appear to be glycoproteins, but only LH has been obtained in absolutely pure form.

In males and females, both FSH and LH are necessary, if puberty is to be established in younger animals, or if the sexual functions are to be maintained in older individuals. Without FSH, the Graafian follicles fail to develop; or if the animal is male, the seminiferous tubules remain inactive. Without LH, on the other hand, ovulation does not occur—i.e., the ripe eggs are retained within the follicles; or in male specimens, the interstitial tissue of the testis remains dormant and fails to produce testosterone. Some evidence indicates that the anterior pituitary also produces a third gonadotropic hormone, *luteotrophin*, which sustains the corpus luteum, especially during pregnancy.

Mammotrophic Hormones. One mammary stimulating hormone, *lactogen*, has been isolated in pure form. This protein compound induces active lactation, but only if the mammary gland has reached a suitable state of development, subsequent to the stimulating influence of estrogen, progesterone, and *possibly* another unidentified pituitary hormone. Lactogen also exerts a distinct influence upon *maternal behavior*, at least in certain animals.

Thyrotrophic and Corticotrophic Hormones. The consistent regression of both the thyroid and adrenalin cortex in animals deprived of the pituitary, indicates that probably the pituitary produces two other hormones: *thyrotrophin* and *corticotrophin.* However, neither of these substances has been isolated, and it is possible that the thyroid- and cortex-sustaining activities of the pituitary extracts may represent an accessory function of some of the other hormones, acting either singly or in combination.

Hormones of the Posterior Lobe. No posterior lobe hormone has yet been isolated in pure form, although several extremely potent extracts have been prepared. All in all, the problem of identifying the posterior pituitary hormones has been very difficult to solve.

Damage to the posterior lobe, or to its controlling center in the brain, gives rise to *diabetes insipidus*, a drastic condition in which the kidney fails to concentrate the urine. The water reabsorption of the nephric tubules is greatly impaired; and such diabetics void as much as 3-10 gallons of urine daily, and must drink corresponding quantities of water to avoid insufferable thirst. Under this condition the urine is quite devoid of sugar and low in salts (or, in other words, insipid).

Crude extracts of the posterior pituitary have been separated into two potent fractions. One fraction is called *oxytocin*, which augments the contractile properties of the uterus, and hence is useful in certain obstetrical cases; and the other fraction is called *vasopressin*, which elicits a constriction of the smaller arteries throughout the body, and hence produces a generalized rise of blood pressure. Vasopressin also counteracts the symptoms of diabetes insipidus; but it is not certain whether these two effects are due to the same or separate hormones.

Other Endocrine Glands. The *placenta* augments the hormonal output of the ovaries, and in addition, produces a potent gonadotrophic hormone, which simulates the action of the luteinizing hormone (LH) of the pituitary. During pregnancy large amounts of this placental hormone are present in the urine—which forms the basis for a widely used *pregnancy test*. Pregnancy urine, injected into a mature but virgin rabbit, stimulates ovulation. A *blutpunkt* on the rabbit's ovary indicates the ovulation, and the female urine usually shows a positive reaction by the end of the sixth week of pregnancy.

The pineal body (Fig. 253) arises as an outgrowth from the roof of the fore-brain, which later becomes flanked by the overgrowth of the cerebral hemispheres. In primitive reptiles, the pineal is associated with the development of a median eye, situ-

ated on the roof of the skull; but in modern vertebrates the pineal body is probably just a vestigial organ (p. 714).

The thymus arises in the embryo as an outgrowth from the gill region of the pharynx, which comes to lie in the upper part of the thorax, flanking the lower part of the trachea (Fig. 253). In microscopic structure, the thymus resembles the tonsils and other masses of lymphoid tissue, although at the time of puberty it usually begins to degenerate. No unequivocal evidence has resulted from many attempts to prove that the thymus is an endocrine organ.

TEST QUESTIONS

1. Slow and enduring coordinations tend to be under hormonal rather than under nervous control. Explain this statement exemplifying the discussion by comparing the flow of saliva with the flow of pancreatic juice.
2. Make a labelled diagram to show the placement of the various endocrine glands in man. Which of the glands are purely endocrine in function?
3. Carefully explain how deficiency, replacement, and overdosage experiments have been used in obtaining evidence that the testis is an endocrine gland.
4. Explain two types of evidence which prove that it is the interstitial tissue and not the seminiferous tubules of the testis which produce the testicular hormone.
5. The secondary sexual features, which differentiate males from females, are related to differences in the sex hormones. Explain this statement in specific terms.
6. Differentiate between estrogen and progesterone on the basis of:
   a. site of production;
   b. chemical structure;
   c. relative abundance during the menstrual cycle;
   d. effects upon the uterine mucosa and mammary glands;
   e. general functions.
7. Carefully explain the relationship between the corpus luteum and: (a) implantation; (b) retention of the foetus in utero; (c) parturition (delivery of the foetus); (d) lactation.
8. Carefully discuss the thyroid hormone with special reference to:
   a. its chemical composition;

b. dietary requirements for synthesis;
c. abnormalities of metabolism;
d. abnormalities of development.

9. Briefly discuss the parathyroids, adrenals (cortex and medulla), islands of Langerhans, and the pituitary (anterior and posterior lobes), specifying in each case:
   a. the hormonal product or products (if known);
   b. the general functions of each hormone;
   c. effects of hypo- and hyperactivity of each gland.
10. Inspect the following list and for each condition specify: (a) the one or more hormones that may be involved; (b) the gland or glands in question; and (c) whether the glands are hypoactive or hyperactive: (1) cretinism; (2) gigantism; (3) persistent glycosuria, emaciation and acidosis; (4) Graves' disease; (5) low blood calcium, with muscular tremors; (6) endemic goiter; (7) exophthalmic goiter; (8) myxedema; (9) fear and anger (as when a cat sees a dog); (10) drastic virilism; (11) diabetes mellitus; (12) diabetes insipidus; (13) very high basal metabolism; (14) delayed growth, retarded sexual maturity, atrophy of the adrenals and thyroid.

FURTHER READINGS

1. *The Hormones in Human Reproduction,* by George W. Corner; Princeton, 1942.
2. *Endocrinology,* by R. G. Hoskins; New York, 1941.
3. *The Physical Basis of Personality,* by C. R. Stockard; New York, 1931.

CHAPTER 22

RESPONSES OF HIGHER ANIMALS: THE RECEPTORS

THE PRECISE and rapid responses of complex animals would not be possible in the absence of a highly developed nervous system; and the nerve cells of the body are constantly engaged in relaying excitations from the sense organs and other receptors to the muscles and other effectors of the body. First to be considered, therefore, are the sense organs and other receptors, which initiate most excitations.

The Sense Organs and Other Receptors. In man, the skin alone houses five distinct kinds of receptors—for touch, pressure, pain, warmth and coldness; and in the head, there are the special sense organs of sight, hearing, taste, smell and balance. Moreover, the muscles throughout the body are equipped with receptors of pressure, tension and pain; and there are other kinds of receptors, which will be mentioned later.

Cutaneous Receptors. Under the microscope a section of skin displays well-defined receptors for touch, pressure, coldness and warmness (Fig. 261, A and B), as well as many *free nerve endings,* which are susceptible to direct stimulation by various pain-inflicting agencies (Fig. 262). These cutaneous receptors can also be located by testing the sensitivity of the skin point by point, on the arm for example. A stiff bristle is used to demonstrate the tactile receptors, and a sharp needle will show the pain receptors; but a blunt metal stylus is required for the pressure and temperature receptors. The stylus is kept at body temperature in demonstrating the pressure corpuscles, but the stylus must be chilled or warmed in finding the

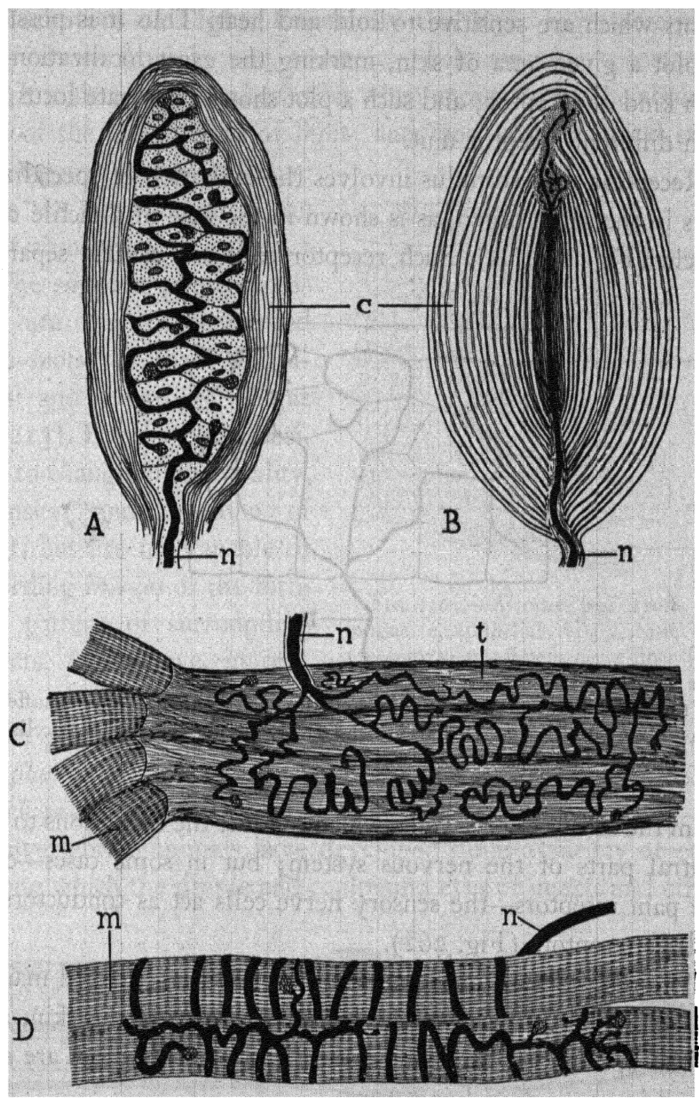


FIG. 261.—Some types of mechano-receptors of vertebrates. A, tactile corpuscle (touch receptor) from the skin. B, Pacinian corpuscle (pressure receptor), found in deeper layers of the skin and in many internal organs. C, Golgi organ (proprioceptor) on a tendon. D, muscle spindle (proprioceptor) in skeletal muscle. n, afferent nerve fibers (the cell bodies of these fibers lie in the sensory ganglia); c, connective tissue capsules; t, tendon; m, muscle fibers.

points which are sensitive to cold and heat. Thus it is possible to plot a given area of skin, marking the exact localization of each kind of receptor; and such a plot shows a separate locus for each different receptor unit.

Reception of a stimulus involves the excitation of specialized cells in the sense organ, as is shown in the case of a tactile corpuscle (Fig. 261, A). Such receptor cells are usually separate

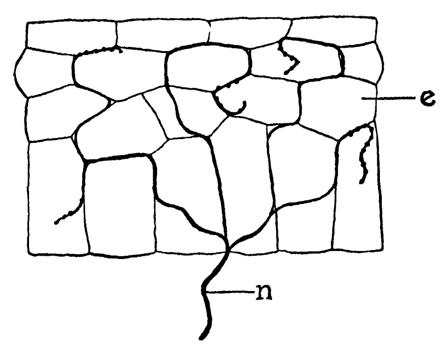


FIG. 262.—Free nerve ending in epithelium. e, epithelial cell; n, afferent nerve fiber, whose terminal branches end freely among the epithelial cells (its cell body lies in a sensory ganglion).

from the sensory nerve cells, which conduct the excitations to the central parts of the nervous system; but in some cases—e.g., the pain receptors—the sensory nerve cells act as conductors as well as receptors (Fig. 262).

The receptors of touch and temperature are restricted mainly to the superficial parts of the body, especially in the skin, and on the lips and cornea; but pressure and pain receptors are also found in many deep-lying parts.

Receptors of Taste and Smell. Each animal discovers and recognizes its food by means of *chemo-receptors,* which are extremely sensitive to chemical stimulation. The taste-buds of the oral cavity (Fig. 263) and the olfactory receptors of the nasal passages (Fig. 264) are representative of chemo-receptors generally; and these structures were discussed previously (Chap. 15).

Receptors of Light, Especially the Eye. Light-receptive cells always contain one or more *photo-sensitive* substances, which undergo chemical reaction when energized by the absorption of the proper kind of light; and most photochemical substances are highly selective as to the wave-length of the light absorbed.

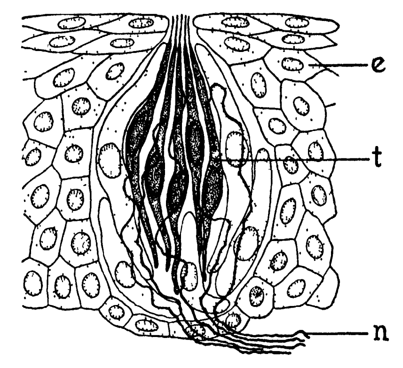


FIG. 263.—A taste bud from the tongue. e, epithelial cell; t, taste cell (receptor); n, afferent nerve fiber (the cell bodies of these fibers lie in a sensory ganglion).

The simplest photo-receptors are the red-pigmented "eye-spots" of many flagellates and unicellular algae (p. 213). Eye-spots are sensitive to changes in the quality, intensity, and direction of light, but are not capable of recording *images* of the form and pattern of surrounding objects. A true eye, in contrast, is a complex organ, which possesses a multicellular *photo-sensory surface*, together with a focusing mechanism, which projects a well-defined image upon the surface.

Invertebrate animals have developed quite a variety of eyes among which the simple and compound eyes of insects and other

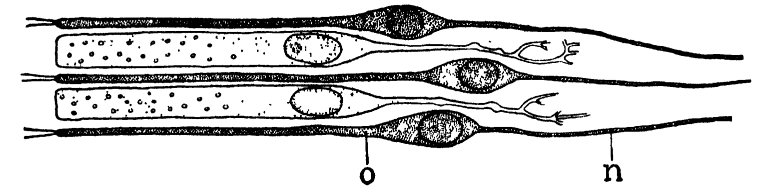


FIG. 264.—Olfactory cells from the nose. o, olfactory cell (smell receptor); n, afferent nerve fiber, the axon of the olfactory cell.

Arthropods are most representative. Essentially the simple eye of an insect consists of a very small *lens* which focuses upon a group of light-sensitive nerve endings. The lens is anchored in a fixed position and cannot vary as to curvature. Consequently

simple eyes possess very little focusing capacity, and do not form very clear images. In fact the compound eye of the Arthropods is not much better in this respect, since the compound eye is merely an aggregate of many simple eyes. Such an aggregate constructs a mosaic of the light and dark regions of the surrounding locale, and is quite effective in detecting moving objects in the environment. A few invertebrates, such as the squid and octopus, possess eyes which can vary the focus for near and distant objects, and these eyes form fairly accurate images of the surroundings.

The eye of man and other Mammals is in many ways like a modern camera, equipped with color film. The human eye (Fig. 265) possesses a high-speed *lens* with an accurately variable focusing capacity; an efficient diaphragm, called the *iris,* which controls the diameter of the *pupillary opening;* and a color-sensitive *retina* (Fig. 265). Also the eye is sturdily built, being protected at the sides and back by the tough opaque *sclerotic coat,* and in front by the strong transparent cornea. The black-pigmented *choroid coat,* which intervenes between the retina and the sclera, functions like the black paint on the inner walls of a camera. The choroid coat absorbs imperfectly focused light rays and prevents them from blurring the image on the retina. And lastly, a free rotation of the eye-ball within its bony socket is effected by six small muscles, which permit the vision to be directed according to the situation (Fig. 265, t).

The lens of the eye *accommodates* for near and distant vision by changes of curvature; and these curvature changes are controlled partly by the elasticity of the lens itself, and partly by the action of the *papillary* muscle (Fig. 265, m). This circular band of muscle surrounds the margins of the lens, exerting a tension on the lens by means of the *suspensory ligament* (Fig. 265). Accommodation for near vision results when the papillary muscle contracts, reducing the tension on the suspensory ligament and lens. When it is released of tension, the elastic lens assumes its unstrained form, which is quite thick and nearly spherical. For distant vision, on the other hand, the ringlike papillary muscle relaxes, increasing its circumference. This re-

stores the strain upon the suspensory ligament and forces the lens to become flatter and broader.

The refractive power of the lens, which effects a precise focusing of the image on the retina, is augmented partly by the

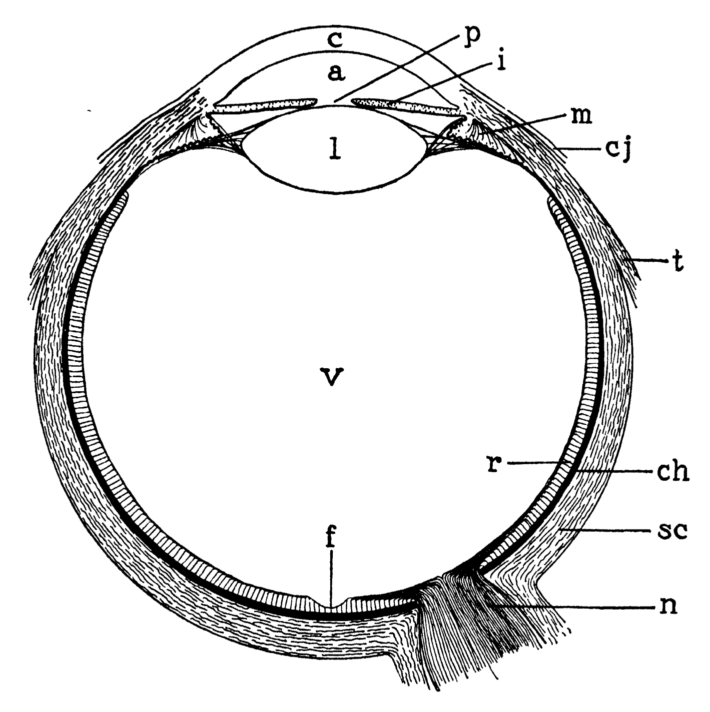


FIG. 265.—Section of the human eye. c, cornea, a, aqueous fluid; p, pupil; i, iris; l, lens; m, muscles controlling the shape of the lens; cj, conjunctiva; t, tendon of one of the muscles moving the eyeball; v, vitreous fluid; r, retina; ch, choroid coat; sc, sclerotic coat; f, fovea centralis, the region of most acute vision; n, optic nerve.

curvature of the cornea, and partly by the refractive properties of the fluids which fill the cavities inside the eyeball. The *anterior chamber,* in front of the lens, contains a relatively nonviscous fluid, the *aqueous humor;* and the *posterior chamber,* behind the lens, is filled with a viscous liquid, the *vitreous humor.*

The *retina,* or true photosensory surface of the eye, is composed of a large number of specialized receptor cells, called

the *rods* and *cones* (Fig. 266). The cones are more numerous in the central area of the retina; and the cones are concerned with ordinary "bright-light vision," in which colors and sharp outlines are clearly appreciated. Vision is most acute in a small depressed area, the *fovea centralis*, where the number of cones is at a maximum (Fig. 265, f).

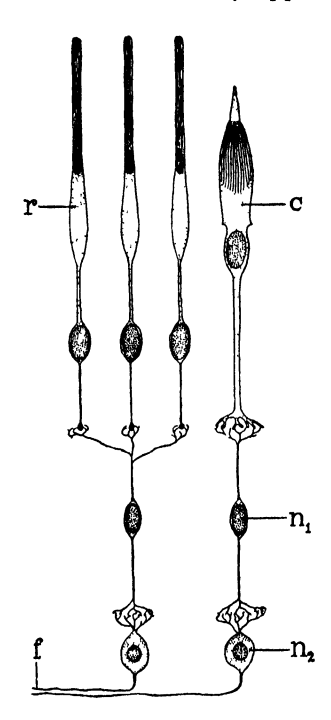


FIG. 266.—Structure of the retina. r, rod; c, cone; n_1, n_2, intermediate neurons of the retina; f, optic nerve fiber, the axon of a retinal neuron.

The rods tend to occupy the marginal areas of the retina, and the rods are employed mainly in "twilight vision." The rods are activated by relatively weak light; but they are not capable of distinguishing colors and sharp outlines—which accounts for the grayness and haziness of vision when the light is dim. The photosensitive substance of the cones has been identified as a vitamin A-protein compound, which decomposes when illuminated, freeing vitamin A. During periods of darkness, this reaction undergoes reversal, so that a maximum sensitivity is found in a dark-adapted eye.

Impulses from the rods and cones are conveyed from the retina by two relays of sensory nerve cells (Fig. 266). The fibers of the second relay converge to form the *optic nerve*, which passes out from the eyeball at a point quite near the fovea centralis. Due to a crowding of the nerve fibers at this point, rods and cones are entirely absent; and this small area of the retina is called the *blind spot*, since images falling upon it are not perceived.

Receptors of Equilibrium. Typically the equilibrium organ of *invertebrate* animals is a hollow capsule, called the *statocyst* (Fig. 267). The statocyst is lined by hair-bearing receptor cells,

and contains one or more grains of sand or other solid *statolyths*. The statolyths are free to fall in any direction, depending upon the position of the animal. Thus as an animal changes its position the statolyths fall upon and stimulate the different hair cells, initiating the movements by which the animal "rights itself."

The lobster and other Crustaceans have sand grains as statolyths, and new sand is taken into the statocyst from the environment each time the animal molts. Thus it is possible to introduce iron filings instead of sand into the lobster's statocyst—in which case the animal will swim upside down, or in any other position, if a magnet is used to counteract the force of gravity.

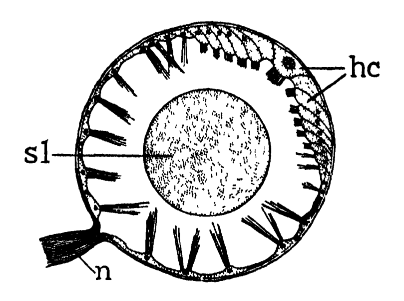


FIG. 267.—Statocyst of a mollusc (Pterotraches). n, afferent nerve fibers; sl, statolyth; hc, hair-cells, the actual receptors. (After Claus.)

The vertebrate organ of equilibrium is a complex structure called the *labyrinth*. This labyrinth consists of three curved tubes, the *semicircular* canals, and two small chambers, the *saccule* and the *utricle* (Fig. 268). The whole system, which develops in close association with the ear, is filled with fluid and lined with hair-cells. The saccule and utricle appear to function more or less like statocysts, but the semicircular canals are concerned with the perception of movement, rather than of position. The different semicircular canals lie in different planes, each at right angles to the others; and when the body starts to move in a given direction, inertia displaces the fluid in some one of the canals, exciting some local group of the hair-bearing receptor cells. Or if the movement stops, the momentum of the fluid displaces the fluid in an opposite direction, which excites some other group of hair-cells.

In fish and other lower vertebrates, the labyrinth is solely an organ of equilibrium; but in land vertebrates part of the labyrinth develops into the *cochlea*, the essential organ of hear-

ing (Fig. 268). The cochlea contains a large number of hair-bearing sensory cells (Fig. 269) which are stimulated by sound vibrations, transmitted from the external air, through the *tympanic cavity*, to the fluid in the cochlea. Perception of the pitch and quality of sounds depends on the fact that the different hair

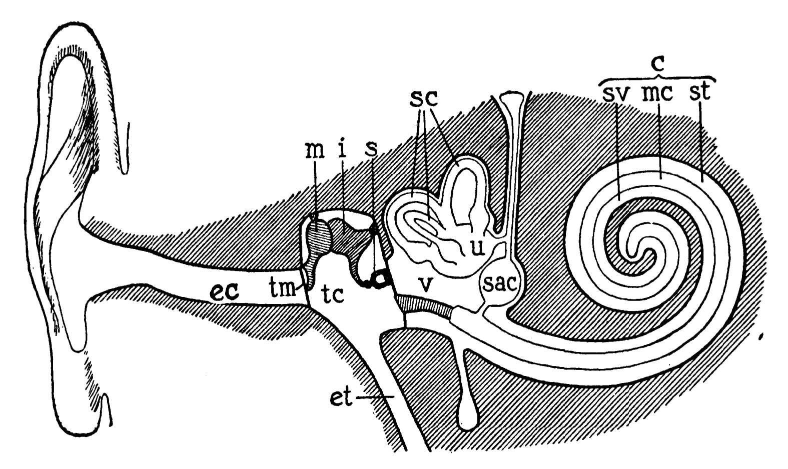


FIG. 268.—Structure of the human ear. The shaded portions with heavy outlines represent bone, the lighter lines represent membranous structures. ec, external auditory canal; tm, tympanic membrane; tc, tympanic cavity; m, i, s, movable bones of the middle ear, which transmit vibrations of the tympanic membrane to the fluids of the inner ear; et, Eustachian tube, opening to the pharynx. Inner ear: v, vestibule; u, utricle; sac, saccule; sc, semicircular canals; c, cochlea; sv, scala vestibuli; st, scala tympani; mc, membranous canal. All the cavities of the inner ear are filled with fluids (lymph), which transmit vibrations.

cells of the cochlea are stimulated by vibrations of different frequencies. Probably insects are the only other animals that possess specialized organs of hearing; but the ears of insects vary widely as to structure and position in the different species.

Proprioceptors. The perception of movement and position of the body *as a whole* is localized in the labyrinth; but each separate muscle and tendon is equipped with receptors, called *proprioceptors*, which play an essential role in co-ordinating the complex movements of the individual body parts. The proprioceptors of the muscles (Fig. 261, D) and tendons (Fig. 261, C)

are sensitive to the changes of tension; and when a muscle is brought into play, its proprioceptors continue to discharge a series of excitations along the sensory fibers of its nerve supply.

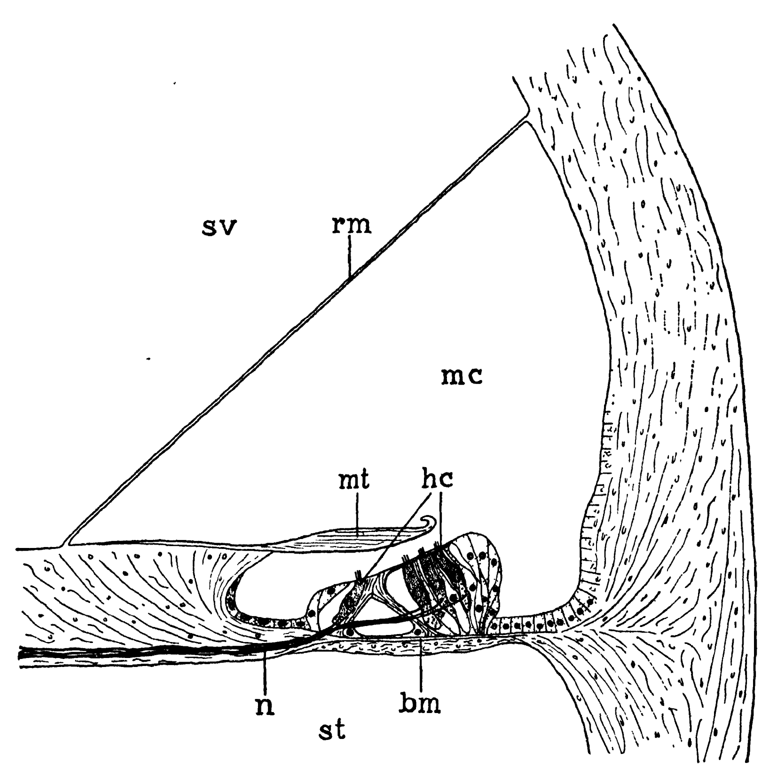


FIG. 269.—Cross-section of a portion of the cochlea. rm, Reissner's membrane, separating the membranous canal (mc) from the scala vestibuli (sv); bm, basilar membrane, separating the membranous canal from the scala tympani (st); mt, membrana tectoria; hc, hair-cells, the actual sound receptors; n, afferent nerve fibers, making up the auditory nerve (their cell bodies lie in a sensory ganglion, not shown in the figure). Vibrations transmitted to the basilar membrane by the fluids of the cochlea cause the sensory hairs to strike the membrane tectoria, stimulating the hair-cells.

Thus each gradation of tension serves to condition the further activity of the muscle and bring it into synchrony with the activities of other muscles. Without the proprioceptors, skilled movements would not be possible; and because of the efficiency of the proprioceptors it is possible to perform skilled movements

without the guidance of the eye—as, for example, the tying of a knot behind the back.

Visceral Receptors. The *interoceptors,* which are localized in the internal organs, play an important role in governing the activities of the viscera. However, the interoceptors of the body are not so well defined as are the various exteroceptors, which have been discussed. The sense of thirst appears to originate in the throat, although the thirst receptors have not been identified definitely. A dearth of water in the digestive tract, and in the body tissues generally, seems to act as a stimulating agency which prompts the animal to seek for and drink the necessary quantities of water.

Hunger sensations originate in the wall of the stomach. The empty stomach is swept by a series of rhythmic muscular contractions, and these *hunger* contractions exert a mechanical action upon the pressure receptors in the gastric wall. Likewise the urge to defecate and to urinate take origin from mechano-receptors in the walls of the rectum and bladder respectively, as a result of tension which develops when these hollow organs become distended by their contents.

Nerve impulses from the interoceptors seldom cross the threshold of consciousness, because such impulses are not usually transmitted to the higher centers of the brain (p. 592). Nevertheless the visceral receptors are most important, as is especially true of the receptors in walls of the blood vessels and heart, which initiate reflexes controlling the blood pressure and pulse rate. Moreover, the receptors in the walls of the lungs play a very important role in controlling the amplitude of the breathing movements (p. 468).

Perception of Sensations. The sense organs merely discharge excitations into the nervous system, and the receptor cells are not *directly* responsible for any sensation which may be experienced by the stimulated individual. What sensation, if any, may result depends not upon the activity of the receptors, but solely upon how the excitations are routed through the nervous system. Only such excitations as are transmitted to the cerebral cortex of the brain succeed in generating any conscious

perceptions; but this phase of responsiveness will be considered in Chapter 24.

Indirectly, however, the sense organs do determine the *quality* of sensations, because each sense organ is connected to the nervous system by a specific set of sensory nerve fibers. The rods and cones, for example, generate sensations of light rather than of sound, because the rods and cones relay their excitations to the brain via the optic rather than the auditory nerves. The nerve fibers and their connections, therefore, determine directly the quality of the sensation; and the stimulation of a certain group of nerve fibers gives rise to the certain kind of sensation, even if these nerve fibers are stimulated artificially by electrical excitation, rather than naturally by impulses from one of the sense organs.

Likewise the *localization* of sensations is a function of the brain; but again the position of the stimulated receptors is an important determining factor. Some sensations, such as pain, are referred to a part of the body itself; but others, such as the warmth of a stove, are referred to the external environment. In either case, however, the location of the stimulated receptors is very important in determining where the sensation is localized by the mind. A cold floor stimulates the thermo-receptors of the soles of the feet, and consequently the coolness is judged to come from the floor; or if one burns oneself, the pain is referred to the injured organ, where the stimulated pain receptors are localized. In the case of pain originating in some of the internal organs, however, the mind is not very accurate in its judgments: quite frequently internal pain is referred to some specific external part of the body.

Judgments as to the *intensity* of a sensation are conditioned largely by the behavior of the stimulated sense organ. Ordinarily when a receptor is stimulated, it discharges not one, but a volley of excitations into the sensory nerves. The stronger the stimulus, the more prolonged is the volley from the receptor; but still more important, the *frequency* of excitations is greater if the stimulus is stronger. Thus a very dim light may stimulate the photo-receptors of the eye to discharge excitations at the

slow rate of about 10 per second, as compared to more than 200 per second, when the light is bright. Furthermore, stronger stimuli usually succeed in stimulating a greater *number* of receptor cells in the sense organ, and thus a greater number of sensory nerve fibers will carry excitation volleys toward the brain. All in all, therefore, the brain cells are influenced by several factors in responding to stimuli of different intensities. With stronger stimuli, greater numbers of nerve cells become involved in spreading the excitation volleys; and the stronger the stimulus, the greater is the duration and frequency in the individual volleys.

Processes of Reception. The essential exciting agency in virtually all types of receptors appears to be either mechanical or chemical. Plainly the touch and pressure receptors are excited by mechanical deformations transmitted through the surrounding capsules (Fig. 261); and it is almost equally obvious that the hair cells of the hearing and equilibrium organs are excited mechanically, by disturbances in the labyrinthine fluids (Fig. 269). The proprioceptors are also excited by the strains of stretch and pressure, while the muscles are doing their work upon the tendons.

On the chemical side, the taste buds and olfactory cells respond very directly to the chemical action of impinging molecules; and probably the thermo-receptors are activated by chemical changes induced in the cells by heat and cold. The pain receptors respond to very strong stimuli of any kind, which indicates that excitation depends upon chemical substances released from damaged cells. And finally, photo-chemical reactions induced by light impinging on the retina, constitute the true exciting mechanism in the rods and cones.

The highly specialized sensory structures of complex animals all seem to have been evolved from the relatively simple mechanical and chemical receptors of lower organisms. The senses have great significance in survival, since the animal must rely upon its senses in the search for food and the avoidance of danger. No organism, so far as we know, has developed a sensitivity to magnetic fields, to radio or cosmic waves, or to infra-

red light; although certain bees are sensitive to ultraviolet light, and bats are able to guide their flight in total darkness because they possess a sensitivity to high frequency vibrations which are *supersonic* to other animals. And despite the fact that all cells are readily excitable by electric currents, no organism has developed specialized receptors for this type of stimulation. Animals have evolved without any direct appreciation of these other forces of the environment, probably because such forces, having little relation to survival, have not played a significant role in *natural selection* (Chap. 26).

TEST QUESTIONS

1. How many kinds of receptors are present in the skin? How is it possible to find where these receptors are localized in any given area?
2. How do pain receptors differ from most other kinds of sensory cells?
3. What is the justification for regarding the eye as a chemo-receptor and the ear as a mechano-receptor? Explain.
4. Make a labelled diagram to show all essential structures in the human eye and state the function of each labelled part.
5. Differentiate between each pair of terms:
   a. the blind spot and the fovea centralis;
   b. rods and cones;
   c. the cornea and the lens;
   d. the choroid and sclerotic coats;
   e. the pupil and the iris;
   f. a statocyst and a statolyth;
   g. the labyrinth and the cochlea.
6. Explain the statement that accommodation for near vision demands work on the part of one of the eye muscles.
7. Explain the fact that the eyes of older individuals suffer a loss in their capacity to accommodate.
8. Explain the functioning of: (a) the saccule and utricle; (b) the semicircular canals; (c) the cochlea.
9. Specify two types of proprioceptors and explain the importance of the proprioceptors in relation to our muscular movements.

10. When a warm object is handled, what factors account for a person's capacity to judge:
    a. the degree of warmness;
    b. the size of the warm object;
    c. the relative position of the object.
11. If the hand is kept in warm water, why does the water soon cease to feel warm?

FURTHER READINGS

1. *Smell, Taste and Allied Senses in the Vertebrates*, by G. H. Parker; Philadelphia, 1922.
2. *Anatomy of the Nervous System*, by S. W. Ranson; Philadelphia, 1943.

CHAPTER 23

RESPONSES OF HIGHER ANIMALS: THE EFFECTORS

THE MOST important effector organs in higher animals are the *muscles* and *glands.* But some complex animals, including both vertebrates and invertebrates, also possess (1) *luminous organs,* which give forth light; (2) *electric organs,* which generate high-voltage electrical discharges; and (3) *pigmentary effectors,* which execute rapid changes in the body color of the animal. Moreover, practically all multicellular animals possess unicellular effectors, such as the amoeboid cells of the blood and ciliated epithelial cells; but these were discussed in Chapter 10.

The Skeletal Muscles. Skeletal muscles (p. 340) execute all external movements of the body and its parts. Typically each muscle has the form of a tough elongate strand which stretches from bone to bone of the skeleton (Fig. 270). Accordingly,

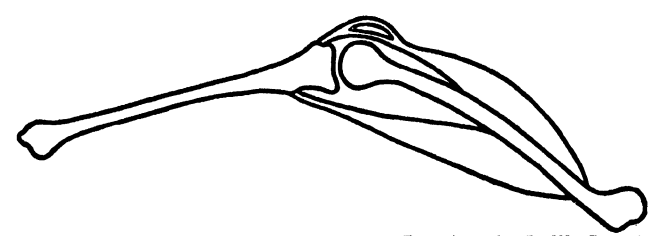
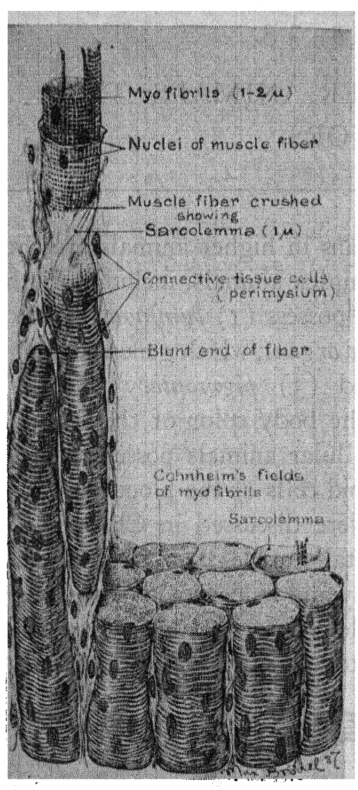


FIG. 270.—Skeletal muscles are attached at their ends to different bones which can move relative to one another. The attachment which is relatively fixed—in this figure, that to the thigh bone (right)—is called the "origin"; the attachment, usually through a narrow tendon, which is more movable—in this figure, that to the shin bone (left)—is the "insertion." Here are shown two muscles which respectively extend and flex the leg at the knee. The "extensor" muscle contains the knee cap in its tendon; the "flexor" muscle has the more usual simple tendon. (Drawn by P. McC.)

when a muscle *contracts*, or shortens, it exerts a force upon some bone, and tends to produce a movement at a joint where the particular bone is hinged to the rest of the skeleton.



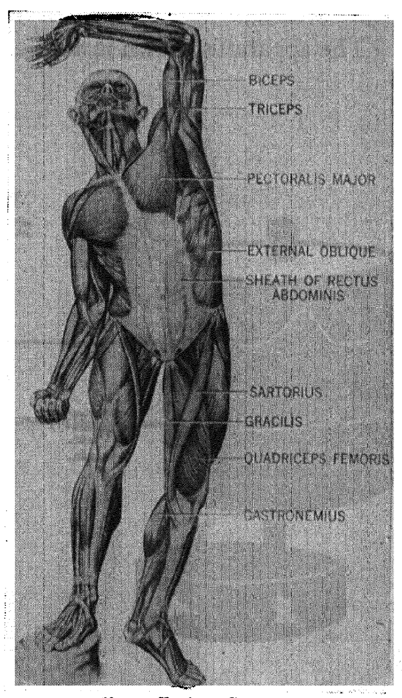
Courtesy of Dept. of Art as Applied to Medicine, Johns Hopkins Medical School

FIG. 271.—Group of fibers of skeletal muscle. Note that the striations of the fibers are due to markings on the myofibrils (top of figure).

Usually the two ends of a muscle are not exactly alike. At the broader end, which is called the *origin*, the many individual fibers (Fig. 271) of the muscle fasten quite directly to the bone; but at the tapered end, which is called the *insertion*, there is usually a *tendon* (Fig. 270). This tough *cablelike* strand of connective tissue intervenes between the fibers and the bone, and transmits the force of the contraction to the bone. Generally the origin maintains a relatively fixed position when the muscle contracts, and thus most of the force of contraction goes to produce a movement of the bone to which the insertion is attached (Fig. 270).

At least two muscles, acting antagonistically, control the movement at any particular joint. In the knee, for example, one set of muscles, called the *flexors*, acts to bend the knee; whereas the *extensors* are used to unbend, or straighten, the joint (Fig. 270). If movement is to occur, the extensors must relax during the time when the flexors are contracting; and conversely, the flexors must relax in synchrony with the contracting extensors—as the joint undergoes bending and unbending.

Each *movement* of the body depends upon a reciprocal action of antagonistic muscles; but the maintenance of *posture* demands that the antagonistic muscles contract *synchronously*. While a person stands, for example, both the flexors and extensors of the knee are contracting simultaneously, locking the joint and converting the leg into a rigid pillar to support the weight of the body. Moreover, an important function of a set of muscles is to *arrest* the movements of the antagonistic muscles. Thus, obviously, the contractions and relaxations of the interacting muscles must be co-ordinated by the nervous system; and each muscle remains inactive until it receives excitations from the nervous system.



From Frohse Chart, Courtesy of A. J. Nystrom Co. Reproduced from MacDougall and Hegner, *Biology*, McGraw-Hill Book Co.

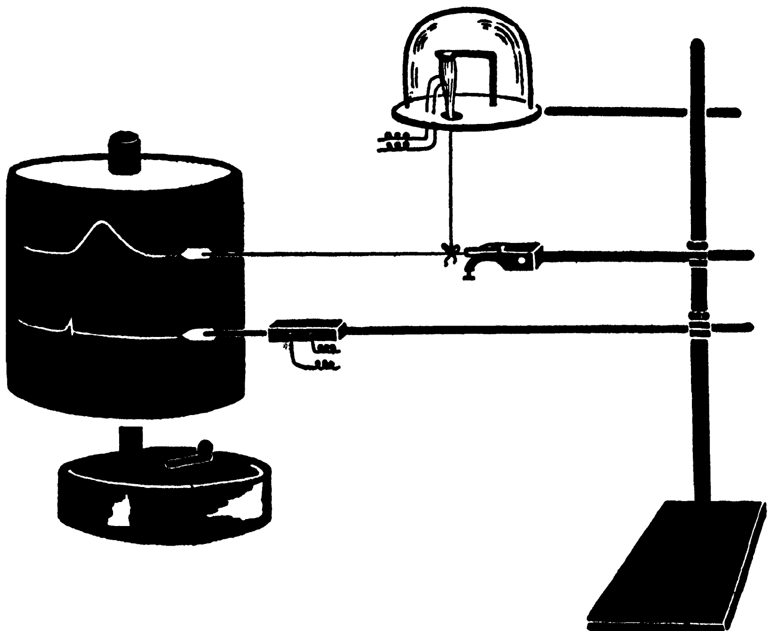
FIG. 272.—Superficial muscles of man, anterior aspect. (Labels added to the chart.)

In an average man, the weight of the muscles constitutes more than 50 per cent of the body weight; and the strength of the larger muscles is very great (Fig. 272). The extensor muscles of the knee, for example, act against an adverse lever ratio of more than 10 : 1 (Fig. 270). Yet an average man weighing 150 pounds can straighten his knees, lifting not only his own body but also that of another man. This means that the right and left extensors together can exert a force of more than 3,000 pounds, or at least 1,500 pounds apiece.

Contraction: The Single Twitch. When a muscle is removed from the body, it retains its capacity to contract, and

may survive for several days. Special precautions to maintain the temperature must be taken in the case of muscles from warm-blooded animals; but "cold-blooded muscles" keep very well at room temperatures. Thus frog muscles are studied most frequently; and usually it is the powerful gastrocnemius, or "calf-muscle," which is selected for experimentation.

The apparatus shown in Fig. 273 is designed to make a record



Reproduced by permission, from *The Body Functions*, by R. W. Gerard, published by John Wiley and Sons, Inc.

FIG. 273.—The frog's gastrocnemius muscle is placed in a "moist chamber" which prevents its drying out and one end is attached to a rigid bar, the other by a thread to a lever which is lifted as the muscle contracts. The electric stimulus is delivered to the muscle through wires; and in the same circuit is included the "signal magnet," shown below the muscle lever, to indicate the instant at which the stimulus is delivered. The muscle lever and the indicator of the signal magnet carry at their tips light paper or celluloid writing points, arranged to touch the surface of the moving cylinder in the same vertical line. At the left is shown a "kymograph," the large drum of which is turned at a constant desired speed by a clockwork mechanism in the base. Wrapped around the drum is a sheet of glazed paper which has been blackened by turning it in a sooty flame. The writing points, by scraping off the soot, trace a white line upon the moving drum. The record of a single muscle twitch is shown. (Drawn by P. McC.)

of a single contraction, or *twitch*, which results when a muscle receives a single excitation. Mounted in a *moist chamber* to prevent drying, the muscle hangs by its origin from an immovable rod (Fig. 273). A cord, tied to the tendon of the muscle, penetrates a hole in the floor of the chamber, connecting the muscle to a lever. The marking point of this *muscle lever* makes contact with the *recording paper*, which covers the surface of a *revolving drum*. Thus each contraction lifts the lever and marks a record of the height and duration of the single twitch.

Usually the muscle is stimulated by an electric shock, which is discharged directly into the muscle, as shown in the diagram; or the shock may be applied to the motor nerve, if it is still connected with the muscle. The instant of stimulation is recorded on the drum by an electrical *signal marker*, which is included in the stimulating circuit. Very frequently the *timing* of the twitch is also shown by a tuning fork, which makes a tracing of its vibrations (usually 100 per second) upon the recording paper; and sometimes a simultaneous tracing of the action current of the muscle is made by means of a galvanometer.

The duration of a *single twitch* in a frog's muscle at room temperature is about 0.1 second (Fig. 274). This time can be subdivided by careful measurements into three periods: (1) the *latent period*, the very brief (0.01 second) interval following stimulation, before any mechanical sign of contraction can be detected; (2) the *contraction period*, the somewhat longer (0.04 second) time during which the muscle is engaged in shortening; and (3) the *relaxation period*, the longest (0.05 second) period, during which the muscle returns to its original length. Usually the *action current*, which is the first indication that the stimulus has excited the muscle, reaches a peak and subsides during the latent period, before there is any mechanical sign of contraction (Fig. 274).

Following a twitch, the muscle consumes oxygen and produces carbon dioxide and heat in excess of the normal resting quantities. This indicates that there is a *recovery period*, which

restores the tissue to its original state. For a single twitch, the recovery period endures for a number of seconds. If a muscle is stimulated repeatedly and rapidly, so that the successive excitations occur before the muscle completes recovery from the preceding twitches, *fatigue* begins to appear. In this case, the twitches become feebler and feebler (Fig. 275); and the fully fatigued muscle will not respond to further excitation. until it

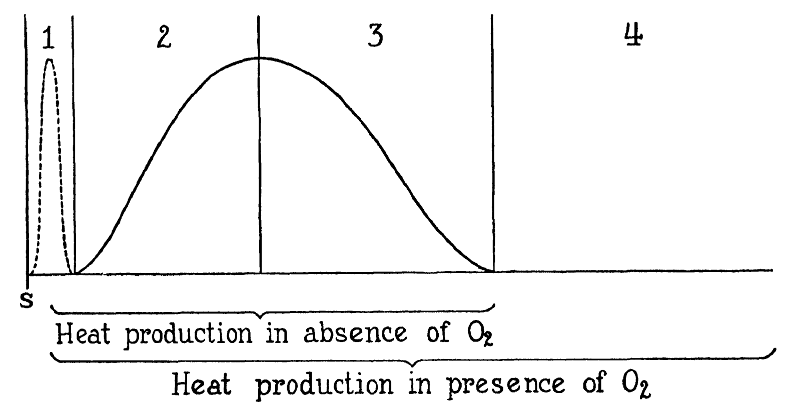


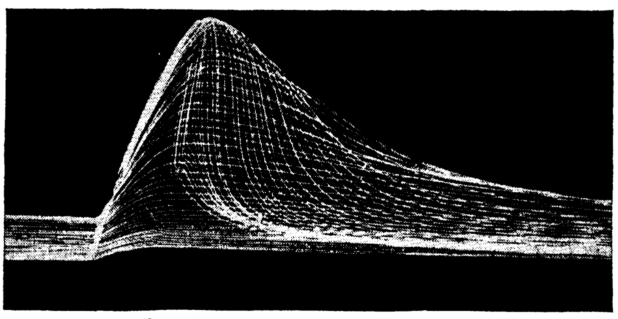
FIG. 274.—Analysis of muscle twitch. The dotted line represents the electrical response (change of electrical potential), the heavy line the mechanical response (contraction and relaxation) of the muscle. s, moment of stimulation; 1, latent period; 2, contraction period; 3, relaxation period; 4, recovery period. (Adapted from Hogben.)

is allowed to rest in the presence of an adequate supply of oxygen.

Contraction: The Tetanus. The duration of a single muscle twitch varies in different animals, being about 0.1 second in the frog; 0.05 second in man; and 0.003 second in certain insects. However, most muscular movements in intact animals are not twitches, but more prolonged contractions, called *tetani.* A prolonged contraction, or *tetanus,* involves not one, but a volley of excitations. During any tetanus the excitations follow each other so rapidly that relaxation cannot occur between the successive contractions. Consequently the muscle remains in a contracted state until the volley ceases. Each separate excitation is, however, accompanied by its own electric discharge; and a con-

tinuous series of action currents can be detected in the muscle, so long as the tetanus continues.

Gradation of Contractions. If a single fiber (Fig. 271) is isolated from the many which compose even the smallest whole muscle, the fiber contracts with maximal force each time it is excited successfully, regardless of whether the exciting stimulus is relatively strong or weak. This *all-or-none law* holds true



Reproduced by permission, from *The Body Functions*, by R. W. Gerard, published by John Wiley & Sons, Inc. Courtesy of Dr. Erma Smith

FIG. 275.—Fatigue. Many successive twitches of an excised muscle, stimulated about 30 times per minute, are more or less superimposed. The earlier contractions reach higher levels and the relaxations occur more quickly. Finally the capacity to contract is abolished completely.

for the single fiber, but it does not apply to the muscle as a whole. The intact muscle gives graded contractions according to the strength of the stimulus applied. Weaker stimuli do not arouse all the fibers of the muscle; and a maximal contraction, in the case of either a tetanus or a twitch, is obtained only when the stimulus is strong enough to bring all the fibers of the whole muscle into play.

Chemical Aspects of the Contractile Process. Even when completely deprived of oxygen, a muscle can perform many twitches, and can sustain a fairly long tetanus. But without oxygen, fatigue sets in prematurely; or to state the matter more precisely, under aerobic conditions a muscle can do about four times more work than under anaerobic conditions.

Chemical analysis of a totally fatigued muscle reveals a number of changes in the tissue. The *glycogen* of the tissue, which

in a rested muscle amounts to some 3 per cent by weight, has virtually disappeared; and the quantity of *inorganic* phosphate compounds has undergone considerable increase. Under anaerobic conditions, there is also an accumulation of lactic acid ($C_3H_6O_3$), in an amount which is equivalent to the missing glycogen.

One reaction which is known to occur while a muscle is working is the breakdown of glycogen into lactic acid. This process of *glycolysis* does not consume oxygen, as may be seen in the following over-all equation:

$$\underset{\substack{\text{glycogen}\\ 0.9\text{ g.}}}{(C_6H_{10}O_5)x} + \underset{\substack{\text{water}\\ 0.1\text{ g.}}}{xH_2O} \rightleftarrows \underset{\substack{\text{glucose}\\ 1.0\text{ g.}}}{xC_6H_{12}O_6} \rightleftarrows \underset{\substack{\text{lactic acid}\\ 1.0\text{ g.}}}{2xC_3H_6O_3}$$

Under aerobic conditions the muscle tissue oxidizes part (about 1/5) of the lactic acid as it is formed, and thus the muscle obtains energy whereby the other part (about 4/5) of the lactic acid is reconverted into glycogen. This reconversion accounts for the fact that lactic acid does not accumulate while a muscle has ample oxygen; and also it explains why glycogen is used up four times faster than normally, when a muscle is deprived of oxygen.

Prior to 1930, glycolysis was thought to supply energy directly to the contraction process; but about this time several poisons were found which completely *inhibit glycolysis without blocking the contractions of the muscle.* In fact when a muscle is exposed to such glycolysis-inhibitors, it behaves quite like one that is deprived of oxygen, except that poisoned muscles fatigue somewhat sooner than those which are asphyxiated. But the fact that a muscle can do considerable work, when no glycolysis is occurring, eliminates this reaction as the primary source of energy in contraction.

Since 1930 the breakdown of a series of organic-phosphate compounds has been found to be the first reaction to occur following any excitation of the muscle. Also it is now known that glycolysis provides the energy through which these important phosphate compounds are resynthesized, subsequent to their

decomposition. Thus a recharging of the contractile mechanism, which follows each contraction, depends upon glycolysis; and the oxidative reactions, which extend throughout the long recovery period, are important mainly because they conserve the glycogen stores of the muscle, by fostering the re-synthesis of glycogen from lactic acid.

The precise nature of the contractile mechanism is altogether debatable, although it is generally agreed that contraction depends upon a sudden folding of elongate protein molecules arranged longitudinally in the myofibrillae. The main protein in muscle tissue is *myosin;* and artificial threads of myosin will contract and expand under a variety of chemical conditions. Furthermore, it is known that myosin itself, as extracted from the muscle, displays a powerful catalytic action upon the decomposition of one of the important organic-phosphate compounds in muscle tissue (p. 165). But whether contraction resembles the release of a stretched spring—in which case muscle metabolism would have the purpose of restoring tension after each recoil—or whether a state of tension results directly from the altered metabolism, cannot be said with any degree of certainty.

The fact that recovery in muscular fatigue depends upon glycolysis and other *anaerobic reactions* is of great practical importance, especially for athletes. Frequently our muscles are called on for tremendous work; and despite the acceleration of respiration and circulation which accompany exertion, the supply of oxygen to the muscles cannot keep up with the increased requirements. During such exertions, the muscles are being recharged largely by glycolysis, and lactic acid accumulates because it is not oxidized as fast as it is formed. But a well-nourished muscle has a good reserve of glycogen, and such a muscle can continue to function until the *oxygen debt* becomes excessive. After a hundred-yard dash, for example, the runner continues to breathe heavily for a number of minutes, and his muscles continue to utilize extra oxygen for almost half an hour. During this time the accumulation of lactic acid gradually subsides, as part is oxidized, and the remainder is rebuilt into gly-

cogen. Thus the net result of muscular exertion is that a certain quantity of the glycogen store of the muscles has been consumed. The muscle may oxidize substrates other than lactic acid, during the resynthesis of glycogen, in which case a greater proportion of the lactic acid is re-converted into glycogen.

Heat Production. The maximal efficiency of a muscle as a machine for delivering mechanical energy is about 40 per cent, which compares very favorably with the 10 per cent efficiency of the best steam engine. This means that under optimal conditions, 60 per cent of the energy expended by a muscle appears as heat, and only 40 per cent as work. However, the heat put forth by the muscles during work is not exactly wasted, since this heat contributes in large measure to the maintenance of the body temperature. The body does not possess any specialized effectors to function as heat-producers, but the muscles are thrown into a special sort of action, namely *shivering*, whenever the body loses more heat than it gains from the general metabolism. None of the metabolic reactions throughout the body is 100 per cent efficient in the fulfillment of its special end, and consequently heat is a by-product given off by all the cells; and since muscle constitutes the bulk of the tissues, the heat donated by the muscles plays a dominant role in maintaining the temperature of the body.

Visceral and Cardiac Muscle. As to energy metabolism, cardiac muscle resembles skeletal muscle; and presumably visceral muscle is also similar, although very little information is available in this regard. But just as there are plain differences of structure among the three types of muscle, so there are consistent differences in their physiological behavior. Skeletal muscle acts most rapidly, completing a single contraction and relaxation in 0.1 second or less—in comparison to 1-5 seconds, for cardiac muscle; and 3-180 seconds, for visceral muscle from various sources.

A continuous mass of either visceral or cardiac muscle responds quite definitely in an all-or-none fashion, so that an excitation of one group of fibers keeps spreading until it involves all the fibers. In the heart this spreading of the excitation is not

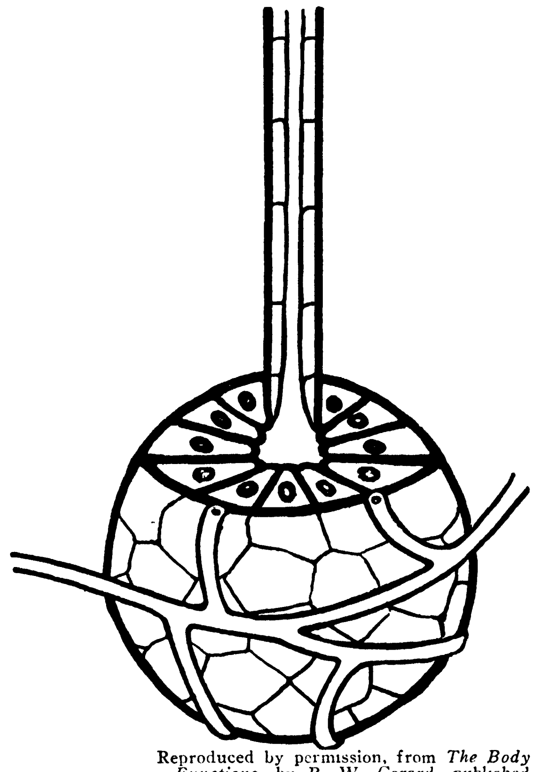
difficult to comprehend, since cardiac muscle represents a continuous syncytium, and the heart is designed to contract as a single unit. The spread of a contraction in visceral muscle may depend upon nervous conduction, in view of the fact that visceral muscle is usually permeated by a fine network of nerve fibers which cannot be removed by dissection.

An outstanding feature of cardiac muscle is the rhythmicity of its action. A frog's heart, for example, if skillfully handled, may keep on beating for more than a month after it has been excised from the body. This means that the contractions of the heart do not depend upon excitations from the central nervous system, although in the intact body, the strength and frequency of the heartbeat are altered appreciably under the action of the cardiac nerves.

Each beat of the heart represents a single twitch; and it is not possible for the heart to undergo a tetanic contraction, because the refractory period (p. 209) of cardiac muscle extends into the contraction period. Consequently a second stimulus never elicits a contraction unless it comes after the heart has started to relax.

Sometimes visceral muscle also contracts and expands in rhythmic fashion, even in the absence of any apparent external stimulation. But the most important characteristic of visceral muscle is its capacity to remain in a contracted or semi-contracted state even while "at rest." A sustained contraction, or tetanus, in skeletal muscle involves a series of excitations coming in usually at the rate of about 50 per second; and skeletal muscle continues to expend extra energy so long as the tetanus continues. But in visceral muscle, a state of sustained contraction, which is referred to as *tonus*, does not involve continuous excitation; nor does tonus demand any extra metabolism above that of the resting state. Thus any degree of tonus in the range between complete contraction and complete relaxation can be maintained with perfect efficiency, and extra metabolic activity is demanded only when the tonus is to be increased or decreased. Visceral muscle is not called upon for quick reversible movements, and consequently there is no need for visceral muscle

to ready itself instantaneously for another full-scale contraction. Thus visceral muscle is able to maintain itself at any given status, and visceral muscle expends energy in shortening or



Reproduced by permission, from *The Body Functions*, by R. W Gerard, published by John Wiley and Sons, Inc.

FIG. 276.—The cells of a gland take substances from the blood in the capillaries on one surface and secrete these or other substances from the opposite surface into the lumen of the gland. (Drawn by E. M.)

lengthening its fibrillae, only when an appropriate stimulus is received.

Glands. These specialized *effectors of secretion* have been considered previously (Chaps. 10 and 15); but a few general points will be considered in the present connection.

The exocrine glands secrete their products into ducts; and usually the active secretory cells are localized in bulbous cham-

bers, called *acini*, at the blind ends of the finer ducts. Raw materials used by the gland-cells in forming their special secretion are brought to the gland by the blood, which circulates through the capillaries, in close association with each acinus (Fig. 276).

Certain glands, such as the sweat and tear glands, synthesize no special substances, but merely extract the components of their juices from the blood. Such glands expend energy in selecting

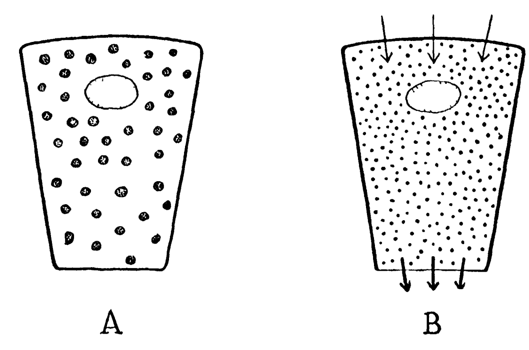


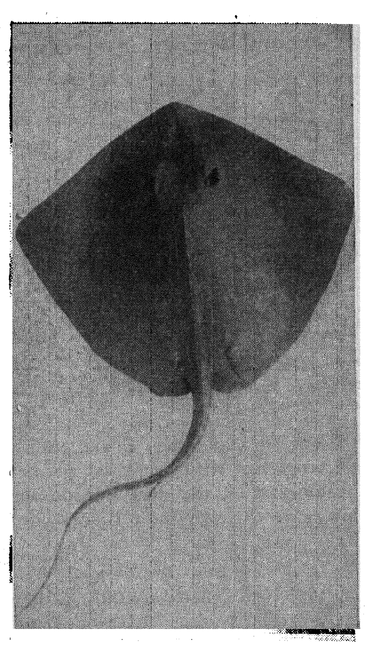
FIG. 277. How secretion may occur. A, the resting gland-cell; B, the gland-cell excited. The increase of osmotic solute, together with increased permeability (or complete breakdown) of the membrane on the duct side of the cell, causes a flow of water from the lymph space through the cell, carrying its secretion out into the duct.

and concentrating their products, since tears and sweat, compared to blood, contain more salts, and scarcely any organic substances, except traces of urea. But most glands also perform the synthesis of specialized secretory products: such as the enzymes of the digestive glands and the hormones of the endocrine glands.

Some glands, especially in the endocrine system, appear to secrete continuously, although this spontaneous activity is subject to change by excitations from the nervous system, or under the action of hormones. But many glands discharge their products only in response to periodic stimulation, in which case each excitation is accompanied by a well-defined action potential.

Precisely how a gland cell discharges its secretion into its duct is not well understood. Secretory granules (p. 219), when present, may disintegrate just prior to their discharge (Fig.

277), or such granules may be swept bodily into the duct through the end of the cell bordering on the lumen. Probably the membrane at this end of the cell momentarily disintegrates, either partially or totally, allowing for the escape of synthesized products which do not ordinarily penetrate the membrane. Glandular activity requires an expenditure of energy, and the rate of respiration in some of the glands is higher than in any of the other tissues of the body.



Courtesy of the American Museum of Natural History, New York

FIG. 278.—Electric or stinging ray (Dasyatis hastata).

Electric Organs. *Galvano-effectors* are used as weapons of attack and defense by several kinds of fish, including the "electric eel" and the "stinging ray" (Fig. 278). Typically the electric organ is built up of disc-shaped cells which are stacked like coins in elongate columns. Each of the effector cells responds to excitation merely by discharging a volley of action currents; but the cells are connected in series, like a string of serially wired batteries, and consequently the action potentials of the individual cells are summated, forming a total discharge of considerable magnitude. In some cases the total potential of the electric organ may exceed 400 volts, which is sufficient to stun, or even kill, a small fish, if it receives the full charge. The amperage from an electric organ is not very great, because the effector cells have a rather limited electrical capacity, and each discharge endures for only about 0.005 second. However, enough current is obtained from the electric organ of a stinging ray to produce a series of brief flashes, when a lamp bulb is brought into the circuit.

Luminescent Organs. Light is emitted by quite a variety of organisms. Certain bacteria and other fungi, luminesce more or less continuously, when oxygen is available; and in this case the light appears to be an incidental by-product of oxidative metabolism. But most luminescent animals, like the firefly, give out flashes of light only when the specialized *luminescent organs* are stimulated. In some cases, the luminescent organs are glands, which give forth luminous secretions; but more specialized organs, such as are found among Insects, Crustacea, Molluscs and Fishes, produce their light intra-cellularly.

Generally speaking, luminescence depends upon the presence of an oxidative enzyme, *luciferase*, which catalyzes a reaction between free oxygen, and an organic substrate called *luciferin*. Both luciferase and luciferin have been extracted from the organs of luminescent insects, but neither has been obtained in pure form. When the two crude preparations are mixed together in the presence of free oxygen, light is given off and water is formed as an end-product. Luciferase differs somewhat from one animal to another, and the same is probably true for luciferin; but the precise color of the light emitted depends upon the type of luciferase which is used. This evidence indicates that the actual emission of light is from the molecules of the enzyme, which become energized during the oxidation of the substrate. However, the energized state of luciferase is short-lived; the enzyme molecules very quickly regain their original properties, and the catalysis continues so long as luciferin and oxygen are available.

Bioluminescence is frequently described as "cold-light," since it is highly efficient and does not dissipate much heat. This is in marked contrast to most light-producing mechanisms, which depend upon the development of high temperatures. Under these conditions much of the energy fails to be transformed into light, and escapes as heat.

Pigmentary Effectors. Chromatophores, which enable an animal to change its color or shade quite quickly and drastically, are possessed by a variety of creatures, including Crustacea, Molluscs, Fish, Amphibia and Reptiles. As to structure, the

chromatophores vary in different animals, but all are mechanical effectors in the sense that the response always involves the movement of pigment granules, which may, or may not, be contained within the protoplasm of the specialized effector cells.

Among invertebrates the chromatophores are usually multicellular organs in which the displacement of the pigment is controlled by muscles. But the chromatophores of vertebrates are single cells (Fig. 279), which are present in enormous numbers throughout the skin. The cytoplasm of these cells is densely packed with pigment granules; and the distribution of the pigment in the cells determines the shade and color of the skin at any particular moment. Most of the pigment cells are *melanophores*, which contain black granules, although some are filled with granules of other colors.

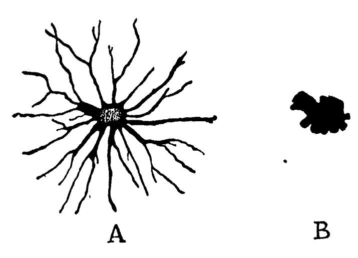
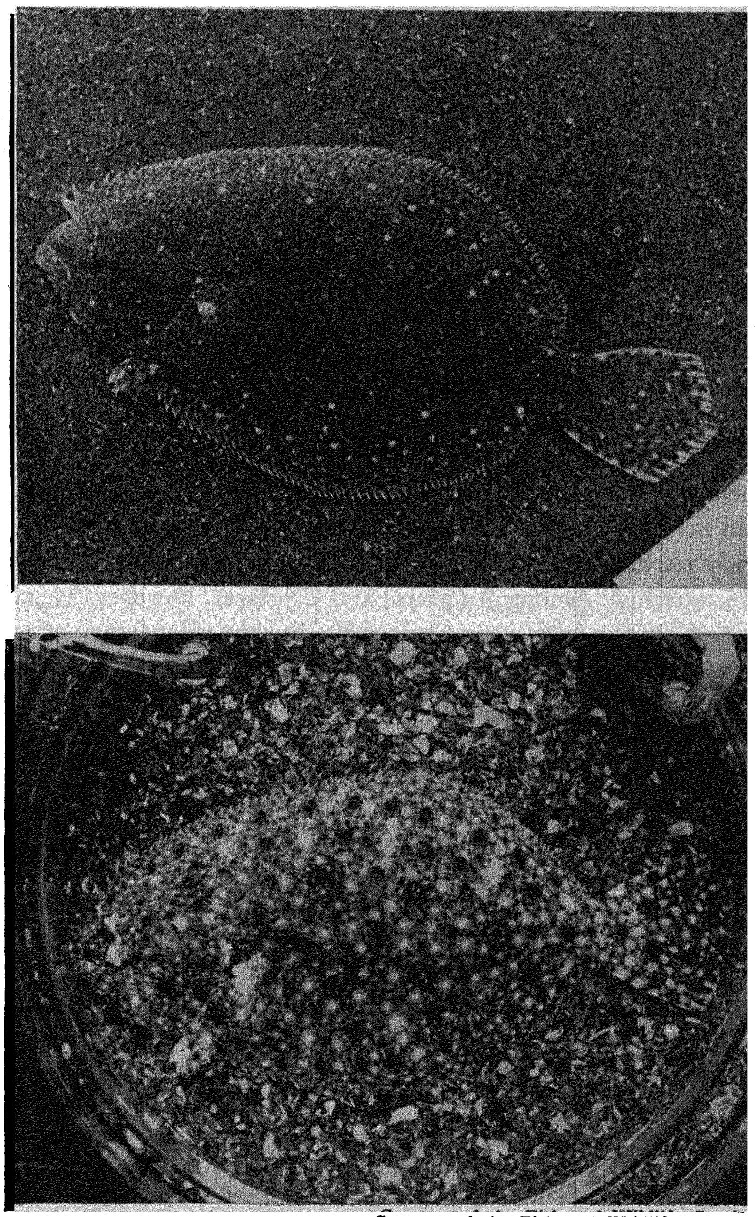


FIG. 279.—Chromatophores containing black pigment, from the scales of a fish (Fundulus): A, expanded; B, contracted. (After Spaeth.)

A scale scraped from the skin of almost any fish provides an excellent preparation in which to study the behavior of the chromatophores under the microscope. Certain drugs, such as adrenalin, excite the melanophores to contract, in which case one can watch the pigment granules flow inward from the many fine branches of the pigment cell until they heap up into a central mass, surrounding and obscuring the nucleus (Fig. 279, B). Or by treating the scale with other drugs, such as acetylcholine, one can watch the pigment granules dispersing into the many finer branches of the cell (Fig. 279, A).

The protoplasmic branches of the pigment cells were previously thought to be pseudopodia, which alternately extend and retract, carrying the pigment with them. But now it is known that the branches are quite permanent, and that the pigment granules ebb and flow through the same channels with each successive expansion and contraction. Thus the pigmentary re-



Courtesy of the Fish and Wildlife Service,
U. S. Department of the Interior

FIG. 280.—Many fish can change their color and color pattern to match their background. Above, flounder against a background of finely mottled sand and mud. Below, same fish against a background of coarsely mottled shells.

sponse probably represents a type of protoplasmic streaming (p. 217), rather than a kind of amoeboid movement (p. 215).

In the intact animal, pigmentary responses are protective in nature, since they provide for changes in coloration in correspondence to changes in the background of the environment (Fig. 280). If a fish, for example, is placed in an illuminated aquarium with a white, or light-colored bottom, the skin of the fish blanches as a result of a regimented contraction of all the melanophores. But if the bottom of the aquarium is changed to black, the skin rapidly darkens, and all the melanophores are found to be expanded.

The normal stimulus which initiates the responses of the pigmentary effectors is light acting through the medium of the eyes and nervous system. Thus a blind fish usually remains permanently dark in contrast to the changing shades of its fellows in the aquarium. Among Amphibia and Crustacea, however, excitations from the eyes are not transmitted to the pigmentary effectors, but rather they act upon the endocrine system. In these animals, therefore, the immediate response is elicited by hormones. And even among Fish and Reptiles, the chromatophores are partially controlled by hormones, although excitations from the nervous system play a more dominant role.

TEST QUESTIONS

1. Name five kinds of effector organs found in fish and other lower vertebrates. Which kinds are also found in man?
2. Distinguish the three kinds of muscle tissue on the basis of (a) structural differences and (b) functional differences.
3. What common structural and functional features are found in all muscle, regardless of type?
4. Specify three functions which could not be achieved unless the muscles were arranged in *antagonistic* groups.
5. Distinguish between a single twitch and a tetanus.
6. Draw a curve to simulate the single twitch of a frog's muscle, designating the name and duration of each part of the curve.
7. Explain the relationship between: (a) the duration of the re-

covery period and the susceptibility of a muscle to fatigue; (b) graded contractions and the all-or-none law.

8. When a working muscle is deprived of oxygen: (a) lactic acid accumulates more rapidly; (b) the glycogen reserves are used up faster; (c) inorganic phosphates accumulate; and (d) the muscle becomes fatigued more quickly and loses its capacity to contract. Explain these facts in the given order, emphasizing the relationships between them.
9. How is it possible for a muscle to do work even though it may have no available oxygen and no capacity to hydrolyze glycogen?
10. Explain how and why a steadily working muscle accumulates an *oxygen debt.* How is the extra oxygen used when a muscle is allowed to rest, and how is this usage related to a partial restoration of the glycogen reserves of the muscle?
11. What is *myosin?* Explain the *dual role* of myosin in relation to the contractile process.
12. Discuss the efficiency of a muscle as compared to other machines.
13. What use to the body is subserved by the energy which escapes conversion into mechanical power during muscular work?
14. Explain the nature and function of shivering?
15. Distinguish between a tetanic and a tonic contraction. Explain why the tonic contractions of visceral muscle are peculiarly well-adapted to the functional responsibilities of this tissue.
16. All glands perform work in extracting the components of their secretions and in concentrating these substances, but some glands also achieve the synthesis of special products. Classify the glands of the body according to this criterion.
17. Briefly discuss electric organs in relation to:
    a. the origin of the discharge;
    b. the magnitude of the discharge;
    c. the usefulness to the possessor.
18. Briefly discuss bioluminescence with reference to:
    a. the occurrence in nature;
    b. the use to the organism;
    c. the metabolic origin of the light;
    d. the efficiency compared to other kinds of light emissions.
19. Changes of color, shade, and pigment pattern in the skin of a fish (Fig. 280), are produced by unicellular effectors. Explain this statement carefully, using a diagram to show how the pig-

ment cells behave when a fish darkens and pales according to the background.

20. To what extent are the pigment cells of the fish, Amphibia and reptiles controlled: (a) by the nervous system; (b) by the endocrine system?

FURTHER READINGS

1. *Muscular Movement in Man*, by A. V. Hill; New York, 1927.
2. *Living Machinery*, by A. V. Hill; New York, 1927.
3. *Color Changes of Animals in Relation to Nervous Activity*, by G. H. Parker; Philadelphia, 1926.

CHAPTER 24

RESPONSES OF HIGHER ANIMALS: THE NERVOUS SYSTEM

THE RECEPTORS and effectors in higher animals are interconnected by the cells of the nervous system, which relay excitations from parts of the body where stimulation occurs to other parts where responses take place. Thus the nervous system *coordinates* activities throughout the body in such a way that each animal displays an integrated behavior as it confronts the problems of survival. Most animal responses are performed without benefit of previous training, because excitations which originate in a certain group of receptors tend to be transmitted by the nervous system to some specific and localized group of effectors. Moreover, such *unconditioned* responses (p. 610) are generally useful to the organism in the sense that they are specifically adapted to the conditions of the particular habitat.

Nerve Impulses. The transmission of excitations is the specialty of nerve cells, and nerve cells transmit excitations at far greater speed than other tissues. Accordingly, *excitations traversing the nervous system are specifically referred to as nerve impulses.*

The speed of the nerve impulse varies in different animals, but it is always great compared to the transmission of excitations by unspecialized tissues. An activated egg cell, for example, propagates an excitation at the rate of only 1 cm. per hour; and thus it is possible to watch the lifting of the fertilization membrane, which accompanies the spreading of the excitation over the surface of the egg. Likewise the sponge, which also lacks specialized nerve cells, transmits excitations at the comparatively

slow rate of 1 cm. per minute. But with the appearance of even primitive nerve cells, such as are found in jellyfish (p. 580), the rate of transmission climbs sharply to 10 cm. per second; and in the well-developed nervous system of the earthworm, the speed is ten times greater. The maximum velocity is reached, however, in the nerves of warm-blooded vertebrates, which conduct impulses at the rate of about 120 meters per second.

Aside from the speed of transmission, nerve impulses are fundamentally similar to excitations in other tissues. Like excitations generally, the nerve impulse is a wavelike protoplasmic disturbance (p. 206) which is always distinguished by well-defined electrical, thermal and chemical changes. Invariably there is a measurable *action current* which keeps precisely in pace with the speeding impulse; and the passage of each impulse involves the liberation of a small amount of heat. At least 90 per cent of this heat comes forth subsequent to actual transmission, while the nerve is consuming extra oxygen and consummating its *recovery.*

Compared to a working muscle, a transmitting nerve expends very little energy, although the total extra heat produced represents much more energy than is liberated by the action current alone. The extra consumption of oxygen and production of carbon dioxide, which result from nervous activity, are so small that they could not be measured until quite recently. In fact the heat produced by a stimulated nerve is equivalent merely to the energy liberated by the oxidation of 0.000001 gram of glycogen per gram of nerve per minute of continuous stimulation. Thus if the nerve contains only 1 per cent of carbohydrate fuel, it could be stimulated continuously for a week without exhaustion; and it is not surprising to find that *nerve fibers are,* in fact, *practically unfatigable,* provided an adequate oxygen supply is available.

Excitability in Nerve Fibers. With proper care, a nerve excised from the body of a cold-blooded animal, such as a frog, will remain alive and exictable for a period of more than twenty-four hours; and excised nerves have been widely employed in

studying the phenomena of excitation. Usually a *motor* nerve, attached to some muscle, is used; and the contraction of the muscle indicates the effectiveness of the stimulus which is applied directly to the nerve. Each motor nerve is made up of many axon fibers (p. 342), which pass to the muscle in a common sheath. These axons, though divorced from their centrons (p. 590), remain alive and excitable for an extensive period after the nerve has been removed from the body.

When such a nerve is stimulated directly with an electric current (Fig. 79), the excitation arises at the *negative electrode*, i.e., at the point where the stimulating current abolishes the positive charges on the outer surface of the fibers (p. 207). Such a depolarization disturbs the balance of forces which maintains the resting structure of the protoplasm, and results in the discharge of one or more impulses from the point of excitation. The action current of such an impulse always flows *toward* the point of excitation, from the outer surface of nearby unexcited parts of the fiber (Fig. 79). Thus a rapid wave of depolarization travels along the length of the fiber; and each depolarized point, as it becomes excited, contributes its share to the propagation of the impulse.

Immediately after transmitting an impulse, each part of a nerve fiber quickly recovers its capacity to be re-excited. In fact the *absolute refractory period* (p. 209) in nerve endures for only about 0.002 second (Fig. 281); but this is followed by a *relative refractory period* (0.012 second), during which the fiber transmits relatively weak impulses. Then, before the fiber returns to its original state, there is a brief *supernormal period*. During the supernormal period the fiber is susceptible to excitation by feebler stimuli; and the magnitude of transmitted impulses is somewhat greater than normal.

Unlike an ordinary electric current, *the nerve impulse does not grow weaker* as the transmitting circuit becomes longer—because new energy is provided to the impulse as it passes each point along the nerve fiber. Moreover, nerve fibers, like muscle fibers, respond in an all-or-none fashion; each fiber discharges

to the maximum of its capacity at the moment of excitation. This does not mean that all impulses are of the same magnitude. In fact the magnitude of an impulse provides a good index of the

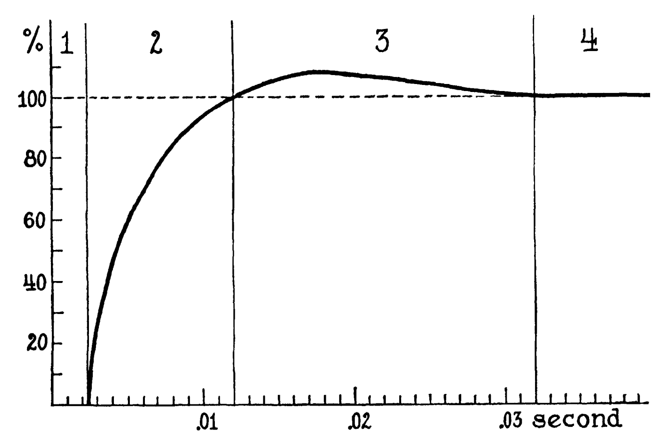


FIG. 281.—Variation of excitability of a nerve after stimulation. Abscissae: time after first stimulation. Ordinates: excitability, expressed as per cent of normal excitability. 1, absolute refractory period; 2, relative refractory period; 3, supernormal period; 4, normal condition. (Adapted from Keith Lucas.)

immediate condition of the transmitting fiber. Thus if one section of a nerve be slightly poisoned (Fig. 282), this section transmits weaker impulses, so long as the toxic condition per-



Reproduced by permission, from *The Body Functions*, by R. W. Gerard published by John Wiley and Sons, Inc

FIG. 282.—The intensity of a nerve impulse traveling from left to right along a nerve fiber is indicated by the height of the action potential outlined above the fiber. Past positions of the impulse are dotted. The slightly shriveled region of the fiber indicates the depressed portion in which the impulse intensity is reduced. (Drawn by P. McC.)

sists; but if impulses manage to traverse a damaged region of a nerve, the impulses regain full intensity as soon as they reach an undamaged section of the nerve.

The Nerve-net of Hydra: A Primitive Nervous System. One of the simplest types of nervous system is found in Hydra and other Coelenterate animals. Hydra possesses a *nerve-net*

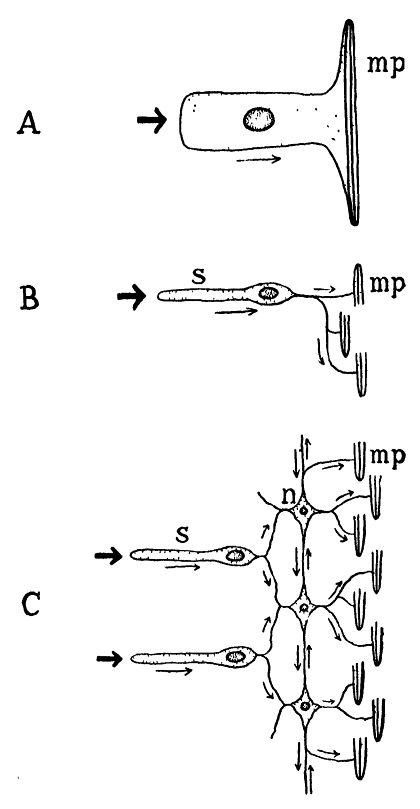


FIG. 283.—The sensory-neuro-motor mechanisms of Hydra. A, independent effector (an epithelio-muscle cell stimulated directly at its free end); B, receptor-effector system; C, receptor-conductor-effector system. mp, muscle processes; s, sensory cells; n, nerve cells. Arrows indicate the points of external stimulation and the directions of transmission of excitation.

(Fig. 283, C) which extends throughout the body and tentacles of the animal. The nerve-net lies in close contact with the mesoglea (p. 352), but its branches make contact with the cells of both the ectoderm and endoderm. Some of these branches are equivalent to the sensory nerve fibers of higher animals, since they receive impulses from specialized receptor cells; but

other branches of the net are motor fibers, since they transmit impulses to the epithelio-muscle cells of the ectoderm and endoderm.

The nerve-net of Hydra is composed of primitive nerve cells, called *protoneurons* (Fig. 284, C) which differ from the *neu-*

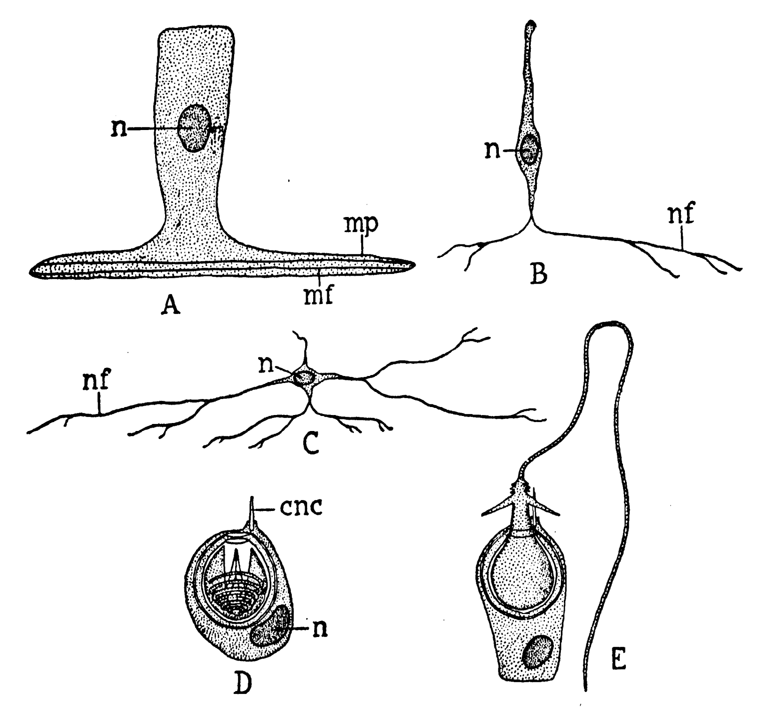


FIG. 284.—Special responsive cells of Hydra. A, epithelio-muscle cell; B, sensory cell; C, one *protoneuron;* D, nettle-cell, undischarged; E, nettle-cell, after discharge. n, nucleus; mp, muscle process; mf, myofibrils; nf, nerve fibers; cnc, cnidocil, or trigger-hair, whose tactile stimulation causes discharge of the nettle-cell. (D and E after Schneider.)

rons of higher animals. Protoneurons may not be discrete cells. In fact the whole nerve-net may represent a syncytium, in which the protoneurons are in protoplasmic continuity with each other. Moreover, protoneurons tend to send out fibers in many directions from the centron (p. 342), rather than along one main *linear* pathway of conduction, as do the neurons of higher animals (p. 585).

In Hydra, impulses from the receptors in any part of the body tend to spread rather indiscriminately in all directions throughout the nerve-net. In fact, any strong stimulus tends to produce a very *generalized* response, such as a contraction of the Hydra as a whole, since a large proportion of the epithelio-muscle cells are thrown into action more or less simultaneously.

There are, however, some factors which tend to *localize* responses, even in Hydra's primitive nervous system. Due to the elongate shape of the tentacles, the nerve-net in these organs runs mainly in a lengthwise direction. This arrangement tends to orient the flow of impulses to and from the tentacles, giving the tentacles some capacity for reacting on an individual basis. Moreover, protoneurons display a relatively *long refractory period*, so that recently excited parts of the nerve-net are not immediately capable of propagating new excitations.

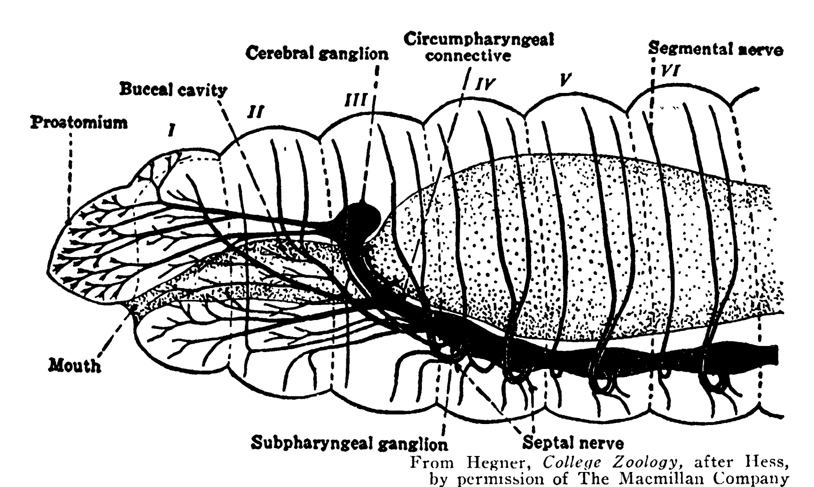
The Nervous System of the Earthworm. Such a diffuse and *uncentralized* nervous system is not characteristic of invertebrate animals generally. In fact many invertebrate animals possess highly centralized nervous systems, as is especially true of the Annelids and Arthropods.

In higher animals, the nerve cells are not scattered throughout the body, but are aggregated in a *central nervous system.* The central nervous system of the earthworm has the form of an elongate *nerve cord* which extends lengthwise through the body. In the earthworm and many other invertebrates, the nerve cord lies *ventral* to the digestive tract, except at the anterior end, where it loops around the pharynx (Fig. 285). Anteriorly the nerve cord terminates in two distinct swellings, the *cerebral ganglia*, which lie dorsal to the digestive tract (Fig. 285); and other swellings, or *ganglia*, occur in the ventral part of the cord, typically one in each *segment* of the body.

The ganglia are very important because these swellings mark the location of the cell bodies, or centrons, of the many nerve cells which compose the whole nervous system. Thus the interconnecting strands between the ganglia (Fig. 285) consist of *nerve fibers* (mainly axons), derived from the centrons in the

ganglia; and likewise the *nerves,* which are associated with each ganglion (Fig. 285), consist of bundles of nerve fibers passing to and from the ganglia.

Central vs. Peripheral Parts of the Nervous System. In such a highly organized system, it is possible to recognize two main functional parts: (1) the *peripheral nervous system* which consists of the many nerves extending out from the nerve cord;



From Hegner, *College Zoology,* after Hess, by permission of The Macmillan Company

FIG. 285.—Side view of anterior end of an earthworm, showing the cerebral ganglion and larger nerves.

and (2) the *central nervous system,* which is the ganglionated nerve cord itself. Each peripheral nerve sends fibers to both the receptors and effectors in a certain segment of the body; and the central nervous system serves as an interconnection between *all* the peripheral nerves. Thus the nerves present in each segment of the earthworm (Fig. 285) are brought into communication with each other, and with all other nerves in the body, by way of the nerve cells of the central nervous system (Fig. 286).

The nerves of the earthworm are all mixed nerves: in that each nerve is made up partly of *sensory* (afferent) *fibers,* which convey impulses from the receptors *toward* the central nervous system; and partly of *motor* (efferent) *fibers,* which always transmit impulses *from* the c.n.s. to the effectors. Thus each

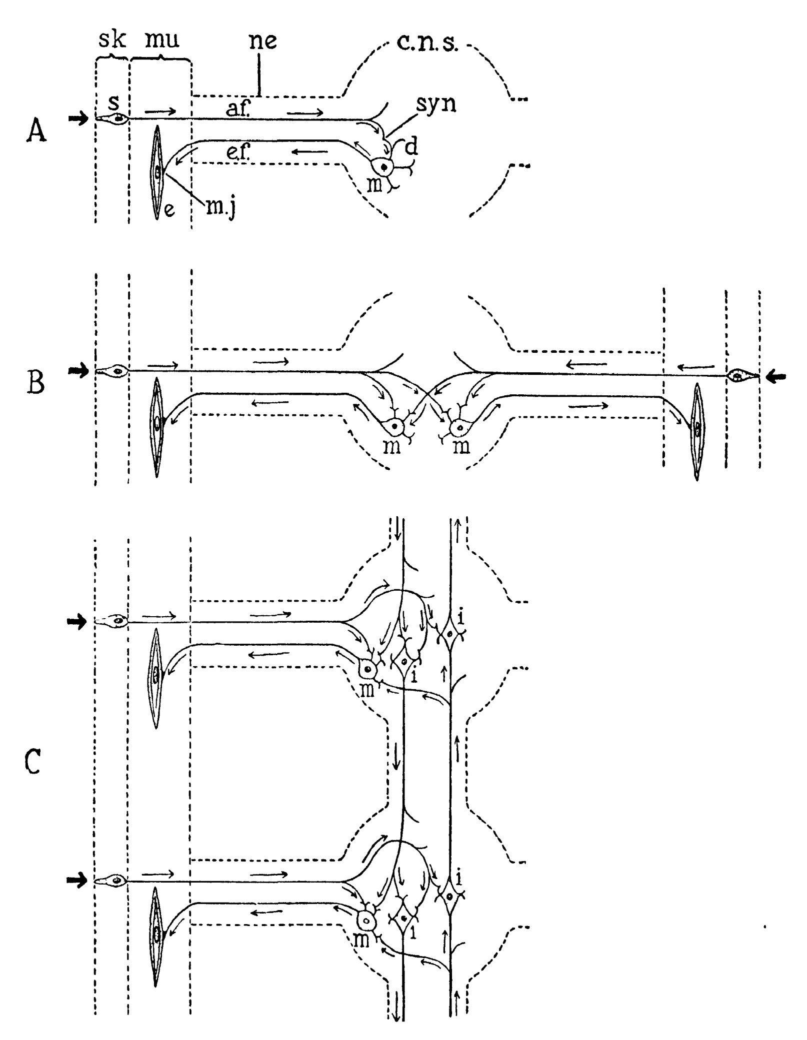


FIG. 286.—Sensory-neuro-motor mechanisms of the earthworm. A, simple reflex arc; B, interconnected reflex arcs within a single segment, involving only sensory and motor neurons; C, intersegmental reflex arcs, involving intermediate neurons. s, sensory neuron; a.f., afferent fiber; syn, synapse; d, dendrites; m, motor neuron; e.f., efferent fiber; m.j., myo-neural junction; e, effector (muscle cell). i, intermediate neuron. sk, skin; mu, muscle layer; ne, nerve; c.n.s., central nervous system. Each ganglion actually contains a large number of neurons, and the branchings and interconnections of the neurons are much more complex than indicated in the diagram.

nerve consists of fibers supplying both the receptors and the effectors in a given region of the earthworm's body (Fig. 286).

The Reflex Arc. As is indicated in Fig. 286, not one, but a series of neurons takes part in relaying impulses to the effectors, whenever the receptors of an earthworm are stimulated. But regardless of the number of neurons, the route taken by impulses in passing from the receptors to the effectors of an animal, is designated as a *reflex arc.* In all cases impulses pass to the central nervous system via afferent fibers, and pass outward from the c.n.s. via efferent fibers.

The many degrees of complexity displayed by reflex arcs are shown in Fig. 286. The simplest arc (Fig. 286, A) is a *unilateral intrasegmental* reflex, which involves just one side of one segment of the animal's body; and another simple arc is a *bilateral intrasegmental* reflex, which involves both sides of any one segment (Fig. 286, B). Similarly it is possible to recognize *intersegmental reflex arcs* (Fig. 286, C)—which may be either short or long; and either unilateral or bilateral in nature.

In the intact animal, each stimulus usually excites many receptors and throws a number of reflex arcs into simultaneous action. Moreover, each sensory neuron makes contact with several *association neurons,* as well as with a number of motor neurons. Association neurons are localized entirely within the central nervous system, and do not send fibers into the nerves. Association neurons make contact with other association neurons, as well as with sensory and motor neurons. In fact the interconnections of the association neurons are so extensive throughout the central nervous system that impulses coming in from any sensory nerve can find their way to *any* motor nerve. However, impulses in all higher animals tend to follow well-defined and localized pathways, which are determined by a variety of factors (see later).

The Neurons of Vertebrate Animals. The neurons of all higher animals are uninucleate cells. Typically each neuron (Fig. 287) displays one or more dendron fibers, which conduct impulses toward the nucleated cell body, or *centron;* and each neuron has one well-defined *axon fiber,* which transmits im-

pulses away from the cell body. Both dendrons and axons may display side branches, or collaterals; and each fiber terminates in a number of twig-like *nerve endings.*

The neurons of vertebrates are essentially comparable to those of invertebrate animals; but the vertebrate nervous system rep-

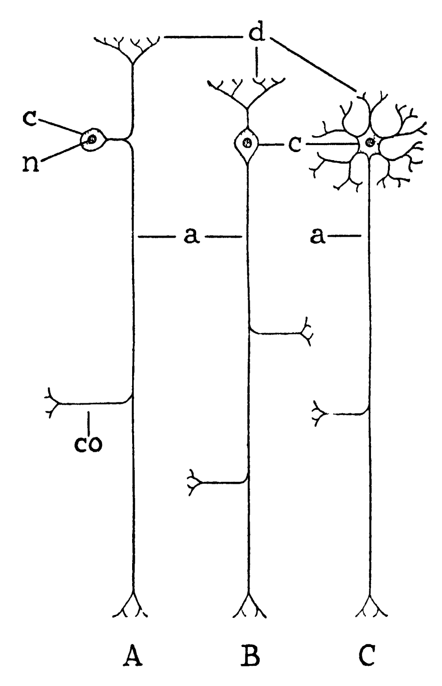


FIG. 287.—Neurons: A, unipolar type; B, bipolar type; C, multipolar type; many variations of these three types occur in various animals. c, centron or cell body; n, nucleus; d, dendrites; a, axon; co, collateral or side-branch of the axon.

resents a much more intricate complex of reflex arcs, as is shown diagrammatically in Fig. 288.

The Synapses and Other Resistance Points in the Reflex Arc. The function of each neuron is simply to relay impulses either to one or more other neurons, or directly to an effector structure. Thus even a relatively simple reflex arc is interrupted by one or more *synapses,* which are the *points of contact between successive neurons.*

Junctures similar to the synapses are also encountered at points where receptor cells make contact with the sensory neurons (Fig. 288), and at points where motor neurons join the

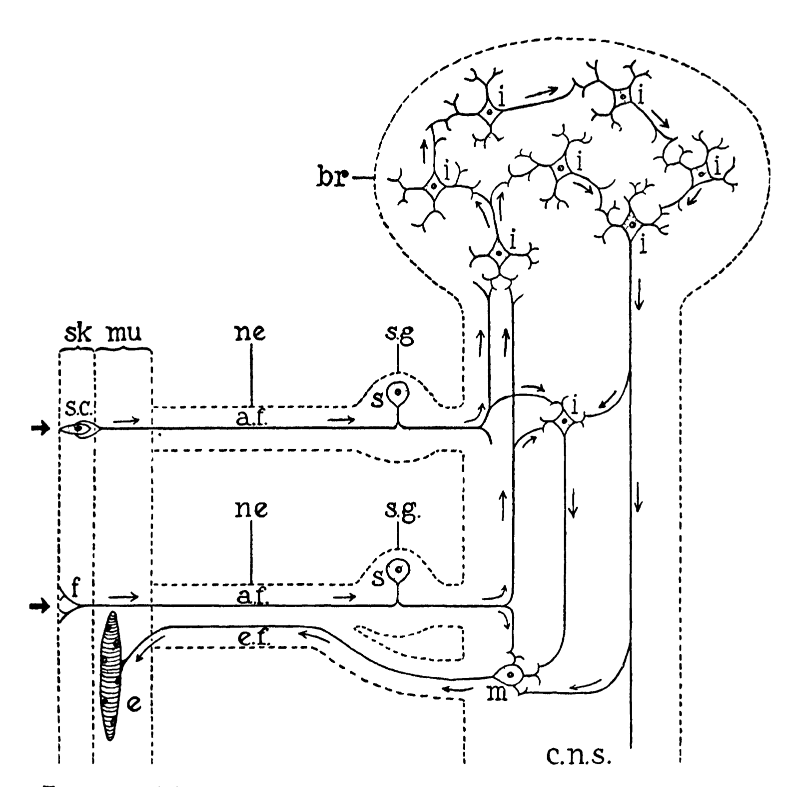


FIG. 288.—The sensory-neuro-motor mechanisms of a vertebrate, including segmental and intersegmental reflex arcs and "long paths" through the brain. f, free nerve ending (dendrites of sensory neuron); s.c., special sense cell, in contact with dendrites of sensory neuron; s.g., sensory ganglion (actually containing many sensory neurons); br, brain; other letters as in Fig. 286.

muscle fibers, or other effector cells. Compared to the synapses, however, these *sensory-neural junctures* and *myo-neural junctures* offer very little resistance to the passage of impulses from the receptors toward the effectors.

The synapses represent points of definite resistance to the flow of impulses through the reflex arcs of all higher animals. Moreover, the resistance varies in different synapses, and conse-

quently the synapses play a very important role in routing impulses through the nervous system and determining the specific responses of the organism.

"One-way" Conductivity: The Law of "Forward Direction." In the intact animal, sensory impulses always travel inward, toward the central nervous system; and motor impulses always pass outward from the c.n.s. However, this law of "forward direction" is determined not by the conductivity of the neurons, but by the fact that *synapses can conduct in one direction only.* An excised nerve will conduct impulses equally well in either direction; but *in the body* an impulse traveling "backwards" through a neuron is always stopped when it reaches a synapse. In other words, impulses may be transmitted from axons to dendrons in successive neurons, but not from dendrons to axons.

The "two-way" conductivity of nerve fibers, in contrast to the "one-way" conductivity of the synapses, may be demonstrated by experiments in which the nerves of an animal such as a frog are exposed and stimulated directly. The simplest method is to expose a motor nerve which consists entirely of efferent axons, passing toward some muscle. When such a nerve is excited—as by pinching—a series of action currents can be detected by a sensitive galvanometer. These impulses pass not only outward toward the muscle (causing it to contract); but they also pass inward toward the spinal cord. However, the backflow of impulses dies out as soon as it reaches the spinal cord. At the spinal cord the impulses encounter the synaptic junctures between the motor neurons and the other neurons of the central nervous system (Fig. 288), and these synapses are not able to conduct in a central direction.

Apparently the dendrons represent the "receptive" portion of a neuron. The dendrons of a post-synaptic neuron may be excited by impulses coming from pre-synaptic axons, but axons cannot be excited by impulses coming from the dendrons.

Synaptic Resistance: Localization of Responses. Even when impulses approach a synapse in the proper direction, they may or may not be transmitted, depending on a variety of fac-

tors. The resistance to the passage of impulses is extremely variable from synapse to synapse, and in any one synapse from time to time. Impulses entering the central nervous system from a stimulated sense organ tend to follow certain *paths of least resistance*, which carry the impulses to some limited and localized group of muscles, or other effectors. In other words, certain reflex arcs offer much less resistance than others, and consequently, the application of a particular stimulus usually results in the performance of one or more definitely localized *reflex acts*.

The role of the synapses in localizing the responses of higher animals is clearly indicated by the effects of certain drugs, which act drastically upon the synapses. Strychnine, for example, greatly *decreases* the resistance of all the synapses, so that all the synapses throughout the nervous system become abnormally and indiscriminately conductive. Consequently, the slightest stimulus, applied to a strychninized animal, gives rise to convulsive contractions involving practically every muscle in the body.

Synaptic Summation. A single stimulus, *applied to an afferent nerve*, may fail to evoke any response, although the stimulus is not too weak to excite the nerve itself. But the same or even a weaker stimulus may evoke the response, if repeated a number of times in rapid succession. This phenomenon of *synaptic summation* indicates that a series of impulses leads to the accumulation of some force or substance, which finally may overcome a synaptic block. The success of a summation depends upon the exact timing of the succession of impulses arriving at the synapses; and this fact is important in determining the reflexes of the intact animal. Ordinarily when a sense organ is stimulated, it discharges not one, but a volley of impulses into the afferent nerve; and in the volley, the frequency of the impulses increases steadily as the strength of the stimulus is raised. Thus a single weak stimulus, *applied to a sense organ*, may fail to evoke a reflex, whereas a stronger stimulus, even when applied just once, may be entirely successful.

Synaptic Fatigue. A *prolonged and continuous* repetition of the same stimulus sooner or later results in a failure of any

response. This block is not necessarily due to a fatigue of the synapses of the particular reflex arc, since the receptor cells themselves may not continue to discharge impulses if the stimulation is continued unduly. But even when the sensory nerve is excited directly by a continuous series of stimuli, a block is finally effected by *synaptic fatigue.* Synapses are much more quickly fatigued than myo-neural junctures, which in turn, are fatigued much sooner than a muscle; and lastly, nerve fibers proper are practically unfatigable. Fatigue of the synapses, like that of other tissues, is a reversible process; and the synaptic block disappears during periods of rest, if an adequate supply of oxygen is available.

Facilitation: Habit, Memory, Learning. Assuming that fatigue is avoided, the mere transmission of a series of impulses across the synapses of a given reflex arc, results in a very enduring increase in the conductivity of this arc to the passage of subsequent impulses. Thus it is always easier for an animal to *repeat* a given response, than to perform the action for the first time. This effect, which is called *facilitation,* is especially characteristic of the brain synapses of higher animals—particularly in higher vertebrates, such as birds and Mammals. This effect is very important, because facilitation is the fundamental basis of such phenomena as *habit, memory* and *learning.* In fact, all *conditioned reflexes,* which enable an animal to *modify behavior in relation to past experience,* are directly dependent upon the facilitation effect.

If fatigue is avoided, facilitation becomes more and more pronounced as the synapses of a given arc continue to be used, until a certain maximum is reached. The degree of repetition required to reach this maximum varies widely from species to species, and from individual to individual in the same species. Moreover, facilitation tends to endure for considerable time—sometimes throughout the life of the individual. The fading of facilitation—and this is the underlying basis of *forgetting* and *loss of habit*—usually proceeds at a gradual pace, during periods when there is a prolonged disuse of the synapses concerned with a particular response.

Functions of the Nerve Cell Bodies. The *centron*, or cell body, of a neuron contains the nucleus of the cell; and if cut off from the centron, the axons and dendrons of a given neuron begin to degenerate after a certain lapse of time. But nerve fibers survive for several days after a severance of their centron connections, and during this period they transmit impulses in normal fashion.

In most neurons, impulses pass directly through the centron en route from the dendrons to the axon; but in the *unipolar* type of neuron (Fig. 287, A), the dendron connects directly with the axon. Accordingly, the centron of such a neuron may be removed without interrupting the normal transmission pathway. This operation does not interrupt the functioning of the unipolar neurons. The operated animal retains all reflexes for more than 24 hours, and therefore it may be concluded that the cell body of a nerve cell—aside from maintaining the nutrition of the nerve fibers—plays no very direct role in the functional activities of the nervous system.

The Nervous System of Man and Other Vertebrates. The vertebrate nervous system is far more complex than that of invertebrate animals, although no fundamental functional differences have been found between the systems. In fact most of our information concerning neurons, synapses, nerve impulses, etc., has been derived primarily from studies on vertebrate animals; and these data have been applied only secondarily to invertebrate animals.

The Central Nervous System. In vertebrate animals, the central nervous system consists of the *brain* and *spinal cord*, which form a thick-walled *tubular* mass of nerve tissue extending lengthwise in the *dorsal* body wall. At its anterior extremity the nerve tube is enlarged and modified, forming the *brain;* but most of the tube forms the *spinal cord*, which has a relatively simple cylindrical form (Fig. 289). The brain lies within a strong (usually bony) encasement, called the *cranium;* and the spinal cord is surrounded by the segments of the *vertebral column.*

The form of the spinal cord does not vary very much in different vertebrates, except in size and length (Fig. 290); but the brain becomes proportionately larger and displays an increasing complexity of form and function in higher vertebrates, especially in man and other Mammals (Fig. 291).

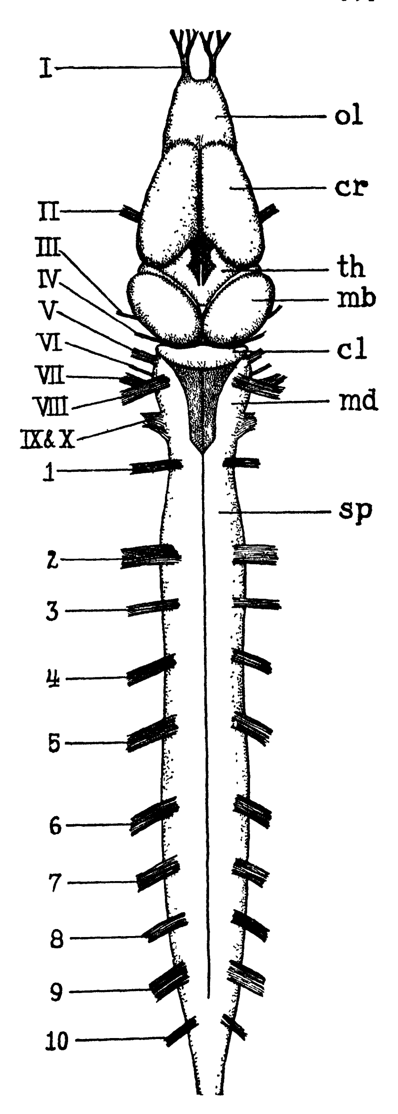
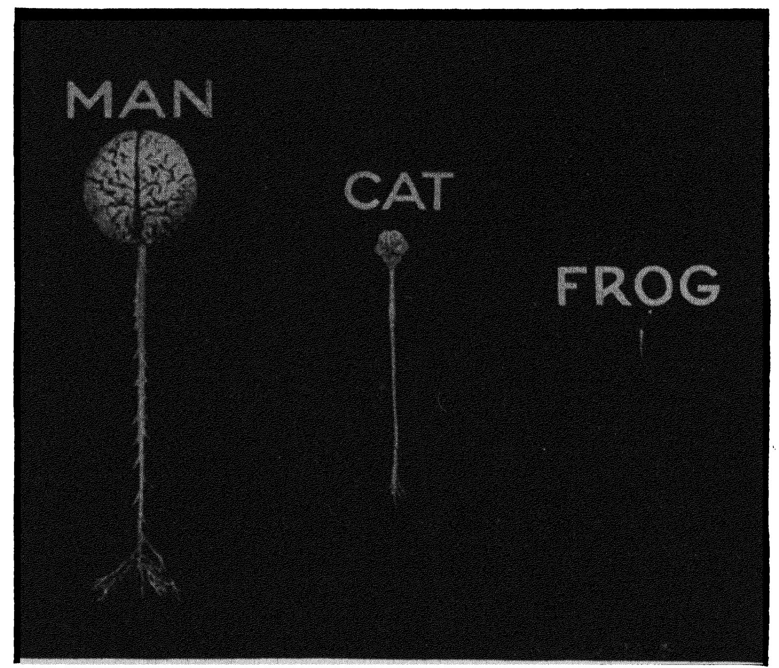


FIG. 289.—Central nervous system of the frog, from the dorsal side. ol, olfactory lobe; cr, cerebrum; th, thalmus; mb, midbrain (optic lobe); cl, cerebellum; md, medulla; sp, spinal cord. I-X, roots of cranial nerves; 1-10, dorsal roots of spinal nerves.

Structure of the Spinal Cord and Brain. A *section* of the spinal cord reveals two regions: (1) an outer mass of *white matter*, composed mainly of axons running lengthwise in the cord; and (2) an inner mass of *gray matter*, consisting mainly of nerve cell-bodies, together with the dendrons and axons which connect up with the centrons (Fig. 292). The grayness of the central area is due to an absence of *myelin*. This whitish lipoid material invests the axons only after they emerge from the gray matter and start running upwards or downwards through the cord. Some of the centrons, especially in the two *anterior horns* of gray matter (Fig. 293), are the cell-bodies of *motor neurons*, which dispatch their axons directly out into the motor nerves; but the

other centrons belong to *association neurons,* which lie entirely in the central nervous system.

The *brain stem,* or lower part of the brain, has much the same structure as the spinal cord; but the walls of the upper part of



From sound film, *The Nervous System,* Encyclopaedia Britannica Films, Inc.

FIG. 290.—Brains and spinal cords of Man, the Cat and the Frog, showing the relative sizes and the proportionately greater development of the brain in Man and the Cat.

the brain are greatly expanded, forming the so-called *higher centers.* The most prominent higher centers—in man and other Mammals—are the *cerebrum* and the *cerebellum* (Fig. 291). The higher centers—particularly the *cerebral hemispheres*—increase in size and complexity from the lower to the higher vertebrates, until in man they overgrow practically all other parts of the brain. In both the cerebrum and cerebellum, there is an external layer of gray matter, called the *cortex,* which completely covers the *outer surface* of these organs. This cortex,

in both the cerebrum and the cerebellum, consists entirely of *association neurons*, which relay impulses to and from the underlying white matter. The cortex neurons are extremely numerous, i.e., several billion are present in the cerebral hemispheres of man. Accordingly it is not possible to trace the exact path of impulses in the higher centers; nor is it possible to pre-

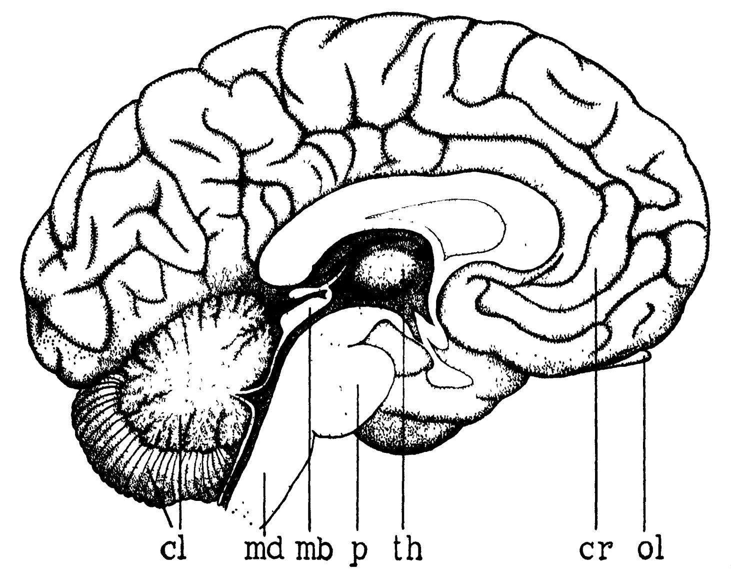


Fig. 291.—Median longitudinal section of human brain. ol, olfactory lobe; cr, cerebrum; th, thalamus; mb, midbrain; p, pons; cl, cerebellum; md, medulla.

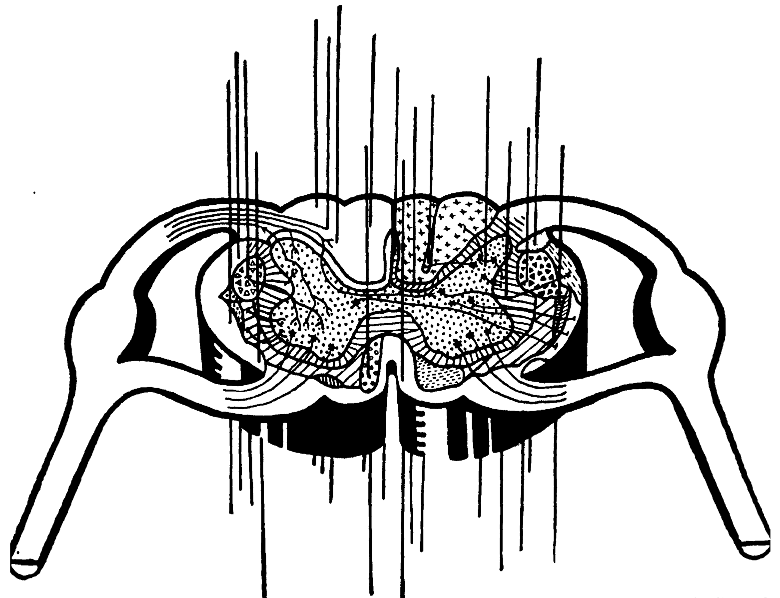
dict the precise outcome of a response, if the reflex arc involves a higher center of the brain.

The cortical regions of the higher centers are very important, because (1) *consciousness* never occurs except in relation to nerve impulses which pass through the cerebral cortex; and (2) the capacity of vertebrate animals to form *conditioned reflexes* is localized mainly in the cortical areas of the cerebrum and cerebellum.

The Cranio-Spinal Nerves: Somatic Reflexes. All movements of the limbs and other external body parts are performed by *skeletal* muscles; and the skeletal muscles are all activated

by motor neurons from the spinal cord and brain. Thus the *spinal nerves* and the *cranial nerves* are directly concerned with all *somatic reflexes*, which determine the activities of the *skeletal muscles*.

The Spinal Nerves. The *segmented character* of the vertebrate nervous system is clearly shown by the arrangement of



Reproduced by permission, from *The Body Functions*, by R. W. Gerard published by John Wiley and Sons, Inc.

FIG. 292.—In this diagram of a section of spinal cord (with the dorsal and ventral roots on each side shown joining to form peripheral nerves), the central butterfly-shaped stippled area is gray matter, the remainder white. Different bundles of fibers in the white matter, which run between fixed regions above and below, are indicated by the various kinds of texture. A few individual nerve cells or fiber connections are indicated. (Drawn by P. McC.)

the spinal nerves (Fig. 289). The spinal nerves originate from the spinal cord in bilaterally symmetrical pairs; and each spinal nerve innervates all the receptors and effectors on one side of one *segment of the body*. Each spinal nerve is a mixed nerve, since it carries sensory fibers from the receptors to the cord, and motor fibers from the cord to the muscles, in a particular body segment.

The junction between each spinal nerve and the cord is effected by *two* roots: a *dorsal root* and a *ventral root* (Fig. 293); and both these roots are different as to function. All *sensory*

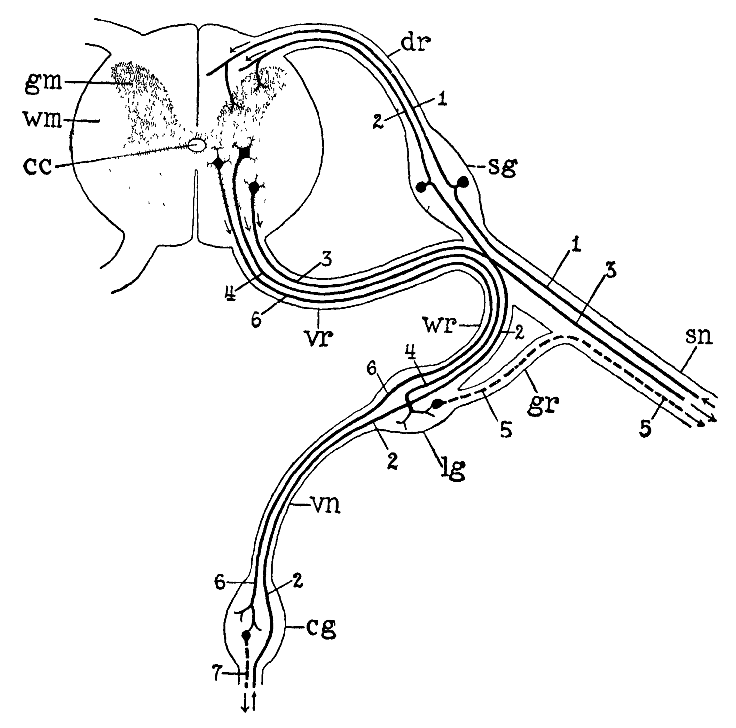


FIG. 293.—Diagrammatic cross-section of the spinal cord, showing the relations of the spinal nerve and sympathetic ganglia on one side. gm, gray matter of the cord; wm, white matter; cc, central canal; dr, dorsal root of spinal nerve; sg, sensory ganglion; vr, ventral root; sn, spinal nerve; wr, white ramus; gr, gray ramus; lg, lateral sympathetic ganglion; vn, visceral nerve; cg, collateral sympathetic ganglion. 1, afferent nerve fiber from receptor in skin or body wall; 2, afferent nerve fiber from receptor in viscera; 3, efferent nerve fiber to skeletal muscle; 4, pre-ganglionic fiber to lateral ganglion; 5, post-ganglionic fiber to smooth muscle or gland of skin or body wall; 6, pre-ganglionic fiber to collateral ganglion; 7, post-ganglionic fiber to viscera. Arrows indicate directions of the nerve-impulses in the fibers.

fibers in the nerve *enter* the spinal cord *via the dorsal root;* whereas all *motor fibers emerge from the cord via the ventral root* (Fig. 293). The dorsal root is also distinguished by an appreciable swelling, the *dorsal root ganglion,* which contains

the *centrons* of all the *sensory neurons* of the corresponding side of a particular body segment. Each of the neurons shown in Fig. 293 represents a type, of which *many* are present in the actual nerve—so that a spinal nerve innervates all the receptors and effectors on the corresponding side in a particular body segment. Moreover, the diagram does not show the association neurons in the gray matter of the cord, which serve to transmit impulses from the sensory neurons to motor neurons, not only in the same segment of the body, but also in segments which lie above and below a particular spinal nerve.

It is not difficult to demonstrate the functional differentiation between the dorsal and ventral nerve-roots. If a *dorsal* root be cut, the animal suffers a unilateral anesthesia, which is limited strictly to one segment of the body. No sensations can originate from the receptors of this segment; nor can any reflexes be initiated, if stimuli are applied in this area of the body. However, the muscles of the segment are not paralyzed, since these muscles can take part in other reflexes, provided these reflexes originate in other segments of the body.

If the *ventral* root of a spinal nerve be cut, there is a localized unilateral paralysis involving just the muscles supplied by the particular nerve. After the operation these muscles cannot participate in any reflex. The segment suffers no anesthesia, however, and reflexes involving other muscles of the body can originate from the receptors of the segment. Essentially, the cutting of one or more *ventral* roots simulates the main symptoms of infantile paralysis; and, in fact, the virus of infantile paralysis does produce a degeneration of the motor neurons which pass out from the spinal cord via the ventral roots.

When a nerve is cut, the fibers which have been divorced from their cell bodies, gradually degenerate. Later, however, a new set of axons and dendrons may grow out along the remnants of the old fibers; and this trail of degeneration and regeneration makes it possible to trace out the origin and distribution of a given set of nerve fibers, even within the mazes of the central nervous system.

The Cranial Nerves. In primitive vertebrates, the cranial nerves develop on a segmental basis; but the brain of modern vertebrates has become so highly modified, that the segmentation is obscured. The cranial nerves originate from the brain—or more precisely, from the sides of the brain stem (Fig. 289). Most vertebrates possess *twelve* pair of cranial nerves; and Table XX shows the cranial nerves of man. Reptiles, birds and Mammals possess the same nerves as man; but only the first ten pairs are fully developed among the fish and Amphibia. Some of the cranial nerves (I, II and VIII) are purely sensory; others are mainly motor (III, IV, VI, XI and XII); and the others (V, VII, IX and X) are mixed nerves, containing sensory and motor fibers in fairly equal proportions. The sensory neurons of the cranial nerves, like those of the spinal nerves, have their cell bodies localized in *ganglia* situated near the nerve-roots.

The cranial nerves function like the spinal nerves, except that in many cases, the cranial nerves are more closely associated with the higher centers of the brain. This is especially true of the main sensory nerves—from the eyes, ears, tongue and nose—in which the fibers are routed quite directly to the cerebral cortex.

Main Conduction Paths: Somatic Reflexes. The simplest possible reflex in a vertebrate animal involves at least one *sensory neuron* and one *motor neuron,* to which impulses are passed directly in the gray matter of the same segment of the spinal cord (Fig. 294, 1). However, such two-neuron arcs play no essential role in behavior, except *possibly* in the case of very simple reflexes like the "knee-jerk" and other proprioceptive reflexes from the tendons and muscles. Most responses in the intact animal involve a number of *association neurons;* and in the case of *suprasegmental reflexes,* which involve the relaying of impulses through a higher center of the brain, the number of association neurons may be quite large (Fig. 294).

The spinal cord serves as the conduction pathway for impulses traveling upwards to the higher centers and downward from the higher centers to effectors situated below the level of the head. In the spinal cord, moreover, impulses of different

TABLE XX

THE CRANIAL NERVES OF MAN

Number	*Name*	*Origin of the Sensory Fibers*	*Termination of the Motor Fibers*
I	Olfactory	Olfactory mucous membrane of nose (smell)	None
II	Optic	Retina of the eye (vision)	None
III	Oculomotor	Proprioceptors in eye muscles (muscle sense)	Muscles which move the eye (with IV and VI). Muscles of accommodation (lens). Iris (constriction of pupil)
IV	Trochlear	Eye muscles (muscle sense)	Muscles which move the eye (with III and VI)
V	Trigeminal	Teeth. Skin of face	Some of the muscles used in chewing
VI	Abducens	Eye muscles (muscle sense)	Muscles which move the eye (with III and IV)
VII	Facial	Taste buds of anterior two-thirds of tongue	Muscles of the face. Salivary glands (submaxillary and sublingual)
VIII	Auditory	Cochlea (hearing)	None
	Vestibular	Semicircular canals, sacculus, utriculus (senses of movement, balance, rotation)	None
IX	Glossopharyngeal	Mucous membrane of pharynx (swallowing reflex). Taste buds of posterior one-third of tongue	Muscles of pharynx (swallowing). Salivary glands (parotid).
X	Vagus	Lungs (reflex control of respiratory rhythm). Mucous membrane of larynx. Arch of aorta (control of blood pressure). Stomach (hunger)	Heart (inhibition). Stomach, small intestine (augmentation of peristalsis). Muscles of larynx (speech). Muscles of esophagus (swallowing). Gastric glands (secretory)
XI	Spinal accessory	Muscles of shoulder (muscle sense)	Muscles of shoulder girdle (shoulder movements)
XII	Hypoglossal	Tongue muscles (muscle sense)	Muscles in tongue (tongue movements)

origins and destinations tend to follow certain rather specific *main fiber tracts.*

Main Sensory Tracts. The association neurons which carry impulses from the *pain* and *temperature* receptors, cross over immediately to the opposite side of the cord and then pass up-

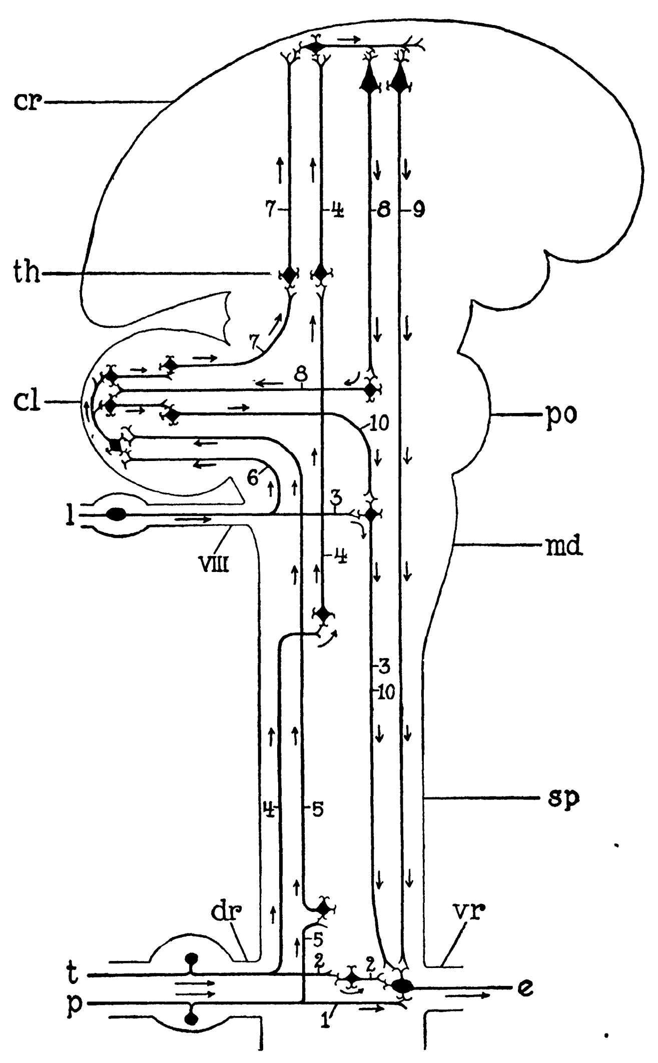


Fig. 294.—Conduction paths in the central nervous system. cr, cerebrum; th, thalamus; cl, cerebellum; po, pons; md, medulla; sp, spinal cord; VIII, eighth cranial nerve (auditory-vestibular nerve); dr, dorsal root of spinal nerve; vr, ventral root of spinal nerve; l, afferent fiber from labyrinth; t, afferent fiber from tactile receptor; p, afferent fiber from proprioceptor; e, efferent fiber to skeletal muscle. 1, two-neuron reflex arc; 2, three-neuron intrasegmental reflex arc; 3, intersegmental reflex arc; 4, main afferent path from tactile receptors (and some other receptors) to cerebrum; 5, main afferent path from proprioceptors to cerebellum; 6, direct afferent path from labyrinth to cerebellum; 7, path from cerebellum to cerebrum via thalamus; 8, path from cerebrum to cerebellum via pons; 9, main efferent path from cerebrum to skeletal muscles; 10, efferent path from cerebellum to skeletal muscles.

wards toward the brain. But impulses from the *touch* and *pressure* receptors, and impulses from the *proprioceptors* of the muscles and tendons, do not cross over, but pass upwards in the cord on the same side; i.e., on the side where the stimulated receptors are located.

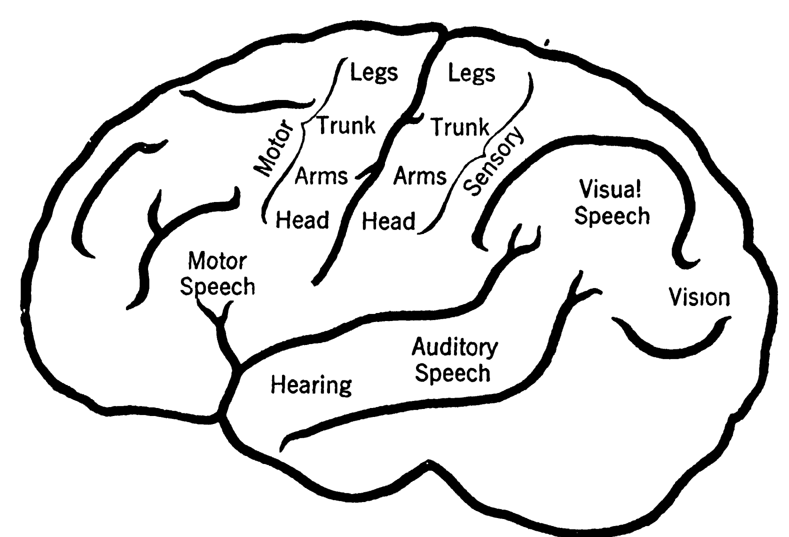
The foregoing localization of the main *sensory tracts* is clearly demonstrated in cases of unilateral injuries of the spinal cord. If only the right side of the spinal cord is crushed or damaged, the subject suffers a loss of "muscle sense" and of touch and pressure sensations, when stimuli are applied on the right side of the body, *below the level of the lesion;* but the loss of temperature and pain sensations is localized on the left side of the body, likewise below the damaged level.

Localization of Impulses in the Higher Centers, Especially the Cerebral Cortex. Proprioceptive impulses passing upwards in the spinal cord are routed mainly to the cerebellum, where the complex movements of the body are co-ordinated; but other types of impulses go mainly to the cerebrum. In either case, however, the crossing-over of *all* impulses is completed by the time they reach the higher centers. Thus pain and temperature impulses are shunted across at a relatively low level, in the spinal cord; but other impulses pass across at a higher level, in the *brain stem.* Each half of the cerebrum and cerebellum, therefore, is concerned with the transmission of impulses which are derived from the receptors on an opposite side of the body.

As is shown in Fig. 295, the cerebral hemispheres sort out the different kinds of impulses and transmit the several kinds through different areas of the cortex. Thus sensations and reflexes initiated in the receptors of the trunk and limbs are abolished by damaging specific areas in the upper mid-region of the cortex; whereas sensations and reflexes originating from the special sense organs are definitely localized in other *specific areas of the cortex.*

The Main Motor (Pyramidal) Tract. The main *motor area* of the cerebral cortex, which sends impulses to the muscles of the arms, trunk, and legs, lies just anterior to the *sensory*

area of the corresponding parts of the body (Fig. 295). Direct stimulation of this motor region produces convulsive movements in the different body parts, according to the focal point of the applied stimulus. Such movements tend to simulate the convulsions which are commonly recognized in epilepsy; and it is gen-



Reproduced by permission, from *The Body Functions*, by R. W. Gerard, published by John Wiley and Sons, Inc.

FIG. 295.—This drawing of the lateral surface of the cerebral cortex of man shows the sensory and motor projection areas which directly connect with the lower parts of the nervous system. The three regions labeled "speech" are primary association areas related to the respective projection areas near by. (Drawn by P. McC.)

erally agreed that epilepsy represents an abnormal hyper-excitability of the neurons of the motor area of the cerebral cortex.

The neurons of the motor area possess very elongate axons which pass downward through the brain stem to all levels of the spinal cord. These axons form a compact bundle of fibers, called the *pyramidal tract*, which begins to cross over in the lower part of the brain stem, at the level of the *pons* (Fig. 291). Thus the pyramidal fibers from one side of the cortex finally reach the motor neurons of the various spinal nerves *on the opposite side of the body*. Injury to the spinal cord, therefore,

results in serious motor impairments, in addition to the sensory losses which were mentioned previously. If only one side of the cord is crushed, all the muscles of that side, in segments below the level of the damage, are divorced from the higher centers, and cannot be utilized for voluntary movements. The paralysis is not complete, however, since below the level of the injury, the intra-segmental and inter-segmental reflex arcs are still intact, permitting the fulfillment of local reflexes—after the animal has recovered from a "temporary shock" which lasts for some hours after the injury.

The Autonomic Nerves: Visceral Reflexes. The responses of the internal organs, in the digestive, respiratory, urogenital and circulatory systems, are performed mainly through the agency of visceral muscle and glands; or, in the case of the heart, by cardiac muscle. These *visceral effectors* differ from skeletal muscles, in that each receives a double set of *motor* fibers from the central nervous system. One set of fibers comes to the organ by way of the *sympathetic* nerves, and the other fibers by way of the *parasympathetic* nerves. Moreover, the sympathetic and parasympathetic fibers always antagonize each other as to their action upon the visceral organ. Thus if one set of fibers augments activity, the other invariably depresses activity in the organ, as may be seen in Table XXI.

By means of such a mutually antagonistic action, the sympathetic and parasympathetic nerves exert a joint control in all visceral reflexes; and thus it is convenient to designate the sympathetic and parasympathetic nerves collectively as the *autonomic nervous system.* Actually the autonomic system is just a physiological subdivision of the peripheral nervous system, and the autonomic nerves, like other peripheral nerves, depend upon the brain and spinal cord for *central connections* in the completion of all reflex arcs. Visceral reflexes, however, generally have their association centers in the brain stem, and visceral reflexes seldom reach the level of consciousness, or voluntary control. Thus the rhythm of the heart-beat, or the peristaltic movements of the gastro-intestinal tract, although regulated by reflexes, cannot be controlled on a volitional basis.

TABLE XXI
ACTION OF THE AUTONOMIC NERVES

Effector Organs	*Sympathetic Nerves (Action of)*	*Parasympathetic Nerves (Action of)*
Digestive tract (stomach, small intestine, colon, rectum)	Depresses activity; slows peristalsis; decreases tone	Augments activity; accelerates peristalsis; increases tone
Heart .	Augments activity; strengthens and accelerates the beats	Depresses; weakens and slows the beat
Blood vessels, especially the arteries and arterioles of skin and viscera	Augments tone; vasoconstriction; elevates blood pressure	Depresses tone; vasodilation; low blood pressure
Muscle fibers in walls of the bronchi and other respiratory passages	Depresses; dilates passages; easier breathing	Augments tone; constricts passages; harder breathing
Iris muscle fibers in eye	Depresses tone; dilates pupil	Augments tone; constricts pupil
Urinary bladder . . .	Depresses tone; dilates bladder	Augments tone; constricts bladder
Hair erector muscle.	Augments tone; erects the hair	Depresses tone; hairs lie flat
Sweat glands .	Augments secretion; profuse perspiration	Depresses secretion; scanty perspiration

One peculiar feature of the autonomic nerves lies in the fact that *motor* impulses, leaving the spinal cord or brain, reach the effector organ, not by way of a single neuron, as in the case of the skeletal muscles, but always by a relay of *two* neurons. In every case the autonomic nerve is interrupted by a motor ganglion in which the *preganglionic neurons* establish synaptic connections with a second relay of *postganglionic neurons* (Fig. 296). Each preganglionic neuron transmits its impulses to several or many postganglionic nerve cells; and this arrangement tends to spread visceral responses rather diffusely, making them less precisely localized than somatic reactions. In the autonomic system, all preganglionic fibers are covered by myelin sheaths; but all postganglionic fibers are non-myelinated.

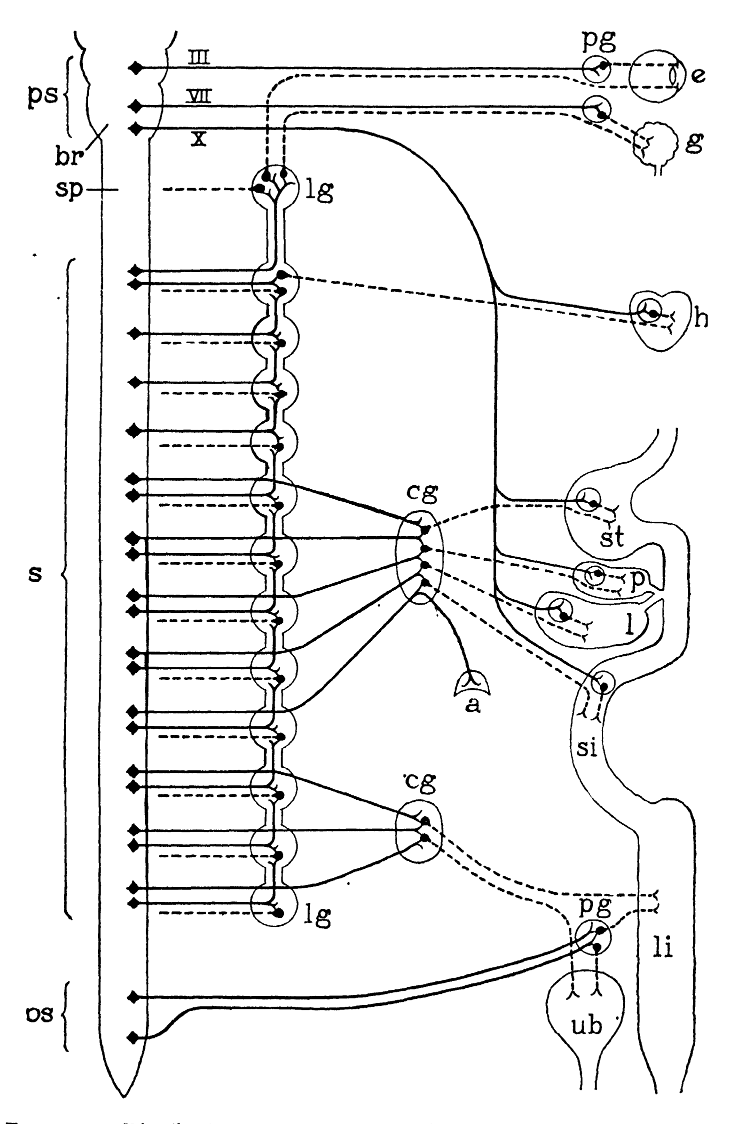


FIG. 296.—Distribution and connections of the autonomic nervous system. The heavy lines represent pre-ganglionic fibers, the dotted lines post-ganglionic fibers. s, sympathetic system; ps, parasympathetic system; br, brain; sp, spinal cord; lg, lateral sympathetic ganglia; cg, collateral sympathetic ganglia; pg, parasympathetic ganglia (and also the ganglia within the visceral organs); e, eye; g, salivary gland; h, heart; st, stomach; p, pancreas; l, liver; a, adrenal gland; si, small intestine; li, large intestine; ub, urinary bladder; III, VII, X, cranial nerves (X is the vagus nerve). The post-ganglionic fibers shown running back toward the spinal cord run in the spinal nerves to the sweat glands, hairs, and blood vessels of the body wall (see Fig. 293).

Most of the ganglia of the *sympathetic* system are *lateral ganglia*, which lie in close proximity to the roots of the spinal nerves, in the so-called *sympathetic chain.* This ganglionated strand of nerve tissue extends along the vertebral column on either side of the body, from the neck, through the thorax, to the abdomen (Fig. 296). A few of the sympathetic ganglia, such as the *coeliac* and other *collateral* ganglia, lie in the abdominal mesentery, some distance from the cord. In either case; however, each sympathetic ganglion exchanges numerous fibers with the nearest spinal nerve. As may be seen in Fig. 293, some of these fibers are sensory fibers derived from receptors in the visceral organs; others are preganglionic fibers passing to the lateral or collateral ganglia; while the rest are postganglionic fibers, which return from the lateral ganglion to the spinal nerve. Thus each spinal nerve distributes quite a number of sympathetic fibers to the visceral effectors (arterial walls, sweat glands and hair-erection muscles) in each segment of the body wall. From the collateral ganglia, however, all the postganglionic fibers proceed to the various visceral organs by way of a number of relatively fine non-myelinated nerves (Fig. 296).

The preganglionic fibers of the *parasympathetic* system are *mainly* distributed by the vagus nerves. This tenth and largest pair of the cranial nerves arises from the brain stem and passes posteriorly through the neck, thorax and abdomen, sending branches to the heart, respiratory organs, and to the gastro-intestinal tract as far as the small intestine. The vagus, however, is not the only channel for transmitting parasympathetic fibers to the visceral effectors. The lens, pupil and salivary glands receive their parasympathetic innervation via other cranial nerves (III and VII); while the urogenital organs and the large intestine are supplied by parasympathetic nerves originating from the spinal cord in the *pelvic* region, close to the posterior termination of the cord (Fig. 296).

The preganglionic fibers of the vagus and other parasympathetic nerves establish synaptic contact with postganglionic fibers in the *parasympathetic ganglia,* which lie very close to the organs which receive the innervation (Fig. 296). Thus all post-

ganglionic neurons in the parasympathetic group possess relatively short axons, which terminate in contact with effector cells in some particular visceral organ.

The Role of Acetyl Choline and Other Chemical Agencies in Synaptic Transmission. In recent years a number of experiments have proved that the transmission of impulses across the synapses and myo-neural junctions of the *autonomic system* depends upon the secretion of chemical agencies, called *neuro-humors;* and these *excitatory substances* appear to be produced locally at the sites of transmission.

The existence of excitatory substances can be demonstrated most readily in the case of the heart. The isolated heart of the frog, for example, will keep beating for many hours. In such a preparation the beat can be slowed by stimulating the cardiac branch of the vagus (parasympathetic) nerve; or the beat can be accelerated by stimulating the sympathetic (accelerator) nerves. If two hearts are arranged in the manner shown in Fig. 297, stimulating the vagus of the upper one produces a retarding effect which is soon transmitted to the lower one. Obviously there are no nerve connections between the two hearts, and consequently the transmission of the vagus effect must depend upon some substance which is carried by the saline perfusion fluid which passes from the upper to the lower heart. Similarly,

Reproduced by permission, from *The Body Functions*, by R. W. Gerard, published by John Wiley and Sons, Inc.

FIG. 297.—The same salt solution passes through the upper heart and then through the lower one, but otherwise the hearts are unconnected. Yet when the vagus nerve to the first heart is stimulated both hearts stop beating. (Drawn by P. McC.)

excitation of the sympathetic nerves in the upper specimen can accelerate the beating of both the hearts, and this indicates that a different excitatory substance is produced by sympathetic stimulation.

Subsequent work resulted in the isolation and identification of the parasympathetic excitatory substance. It proved to be a fairly simple nitrogenous compound, named *acetylcholine*. Acetylcholine has a very powerful excitatory action upon ganglionic synapses and myo-neural junctures throughout the parasympathetic system generally; and this neuro-humor is believed to be produced during the normal transmission of impulses in the parasympathetic system. A special enzyme, *cholinesterase*, has been identified in many of the body tissues. This enzyme rapidly hydrolyzes acetylcholine, and probably serves to limit the duration of the excitatory effect when acetylcholine is liberated by the parasympathetic nerve endings.

The sympathetic excitatory agent has been named *sympathin*, although it has not been isolated as a specific compound. Sympathin exerts an adrenalin-like action upon the ganglionic synapses and myo-neural junctions of the sympathetic system (p. 602); but since significant quantities of sympathin do not ordinarily reach the general circulation, this compound tends to have a more localized action than adrenalin.

Chemical Theory of Synaptic Transmission. The identification of specific neuro-humors which dominate synaptic excitations in the autonomic system has given rise to the hypothesis that the same or similar substances may also play an important role at the synapses of the central nervous system. Transmission across the synapses is certainly different from the conduction of impulses along the nerve fibers proper. The synapses will conduct in one direction only and they impose a definite delay (*synaptic delay*) in the transmission of all impulses. Frequently the volley of impulses discharged by the post-synaptic neuron endures for a short period after the pre-synaptic neuron has ceased firing (*after-discharge*); and the frequency of impulses in the post-synaptic volley is often quite different from the frequency in the pre-synaptic volley. And finally summation phe-

nomena are much more characteristic of synapses than of other parts of the nerve cell.

Although the chemical theory of synaptic transmission offers a logical explanation for these and several other synaptic characteristics, more direct evidence is needed before the hypothesis can be accepted with reference to the central nervous system.

Behavior. To analyze the full pattern of responses in the individual animal; or in short—to study the behavior of the organism as a whole—would be to usurp the subject matter of *psychology*. Consequently the present account of behavior will be limited very strictly to considerations of general biological importance.

The modern tendency is to explain all *discontinuous responses* (p. 205) in terms of the intricate interconnections of the nervous system. The nervous system consists essentially of a very extensive network of reflex arcs, some simple and others very complex, but all interrelated both anatomically and functionally, via a multitude of association neurons in the brain and spinal cord.

Vertebrate animals are able to perform quite a number of fairly complex, though highly standardized responses, even without any preliminary training or conditioning. The human infant, for example, immediately begins responding to the manifold stimuli of the environment by performing a number of complex actions, and the child executes these responses just as well initially as subsequently. The infant starts breathing; it sucks upon the breast; it salivates when anything is placed in the mouth; and so forth. In fact, even before birth, while the foetus is in utero, many visceral responses, such as the heartbeat and the peristaltic movements of the gastro-intestinal tract—and some somatic responses, such as movements of the arms and legs—begin to take place at appropriate stages in development.

Unconditioned Reflexes. Regardless of complexity, any standardized response to a standardized stimulation, which can be executed by an organism without benefit of previous experience, is called an *unconditioned reflex*. In higher animals such responses indicate the existence of a number of highly conductive

reflex arcs, in which the synapses offer virtually no resistance to impulses, even *in the absence of the facilitating effects of previous transmission.*

Depending on complexity, *unconditioned reflexes* are classified as (1) *simple reflexes*, which involve only a few quite localized receptors and effectors; and (2) *compound reflexes*—otherwise known as *instincts*—which involve many receptors and effectors, acting in sequence. Essentially, it is thought, an instinct represents a train of interlocking simple reflexes, each touched off by its predecessor. However, the line of distinction between simple and compound reflexes is quite arbitrary. In man, for example, coughing, salivating, and swallowing are usually classified as simple reflexes, whereas sucking, chewing and spitting out disagreeable material are regarded as instincts.

A conspicuous feature of unconditioned reflexes is their survival value to the organism. In most cases, they serve in one way or another to secure the welfare of the individual and to foster the perpetuation of the species. This characteristic, however, does not imply any consciousness on the part of the animal as to the consequences of its acts. It merely means that different organisms have developed a structural and functional capacity to execute certain self-preserving responses, and these organisms continue to survive and perpetuate themselves, each according to its kind.

The lack of any "conscious purpose" in unconditioned reflexes is clearly shown by the fact that their "usefulness" applies only under the natural conditions of the animal's age-old habitat. When some feature of the natural environment is changed, the animal still responds in the same old way to the same old stimulus, even though the response may now be useless, or even injurious. Moths, for example, always fly toward the light. Under primeval conditions this is probably a useful response, since the moth is a nocturnal flyer and depends upon white or light-colored flowers as a source of nectar. But with the introduction of fires and lamps into the moth's environment, this response becomes virtually suicidal—but nevertheless it persists. The moth flies into the flame for the same reason that it flies to a white

flower—not because it knows the flower to be nutritious, nor because it thinks the flame to be a flower—but because its eyes, nervous system and wing-muscles are so connected that an unequal illumination of the two eyes sets up reactions which automatically turn it toward the light. Likewise, a majority of the complex and seemingly purposeful actions of lower vertebrates —such as fish, Amphibia and reptiles—are machinelike and unvarying in nature. And even in the birds and Mammals—many of the reactions most essential to survival are purely unconditioned, i.e., quite independent of experience and learning.

Modifiability of Behavior: Conditioned Reflexes. In higher animals especially, the same stimulus does not invariably elicit the same response, and there are a number of factors which may, to a greater or lesser extent, modify the outcome of a given stimulation. *Combinations* of two or more stimuli, applied simultaneously or in close succession, often change the response that would be evoked by either one alone. This change may consist in (1) *reinforcement,* i.e., a stronger response than usual; (2) *inhibition,* a weaker response, or none at all; or (3) *modification,* a different response than either stimulus alone would evoke. All these phenomena depend upon the particular connections, within the nervous system, of the reflex arcs involved; and also upon the time and intensity relations of the nerve-impulses traversing the various arcs. Thus the behavior of an individual is determined not by a single stimulus, but by the entire *situation,* i.e., the total pattern of stimuli impinging on the animal at any given moment.

All learned responses of an animal, the fulfillment of which depends upon previous training or experience, fall into the category of *conditioned reflexes.* Such conditioned reflexes are frequently extremely complex and indirect; and the many factors which determine this type of behavior are difficult to investigate experimentally. However, the classical experiments of Pavlov, which were mentioned previously, have served to initiate many experiments on the learning process.

Conditioned responses are superimposed upon the unconditioned reflexes of an animal, such as a dog, by a process of sub-

stituting one kind of stimulation for another. In an unconditioned dog, for example, only the actual presence of food or other material in the mouth will elicit the salivation reflex; but if another kind of stimulus is applied each time the animal is fed, soon the foreign stimulus alone will evoke a flow of saliva. In other words, the dog has "learned" to salivate at the sound of a dinner bell, or at the smell of a tasty morsel—or whenever any other stimulus, however bizarre, is applied repeatedly, in close association with the original stimulus.

The capacity to form conditioned reflexes is more highly developed in vertebrates, as compared to invertebrate animals; and in birds and Mammals, as compared to lower vertebrates. Among vertebrates, the conditioning potentiality is definitely related to the development of the cerebral cortex; and if this part of the brain is destroyed, the animal loses all previously acquired learning as well as all capacity for forming new conditioned responses. Apparently impulses from all the receptors of the body converge upon the association neurons of the cerebral cortex, and tend to be shunted into motor pathways which at the moment are superexcitable because they are simultaneously engaged in carrying out some well-established reflex. Consequently other stimuli acting simultaneously with an original stimulus tend to establish an associative connection with the original stimulus. Furthermore, any repetition of this association tends to *facilitate* the new connections and to establish the "habit" of the new response.

Birds and Mammals stand strikingly above all other animals in their ability to learn. Among Mammals, an especially high degree of educability is found in some of the larger carnivores and herbivores, such as dogs, horses, and elephants. These animals are not intelligent because they are domesticated—they are domesticated because of their intelligence, i.e., their ability to be trained. The highest development of intelligence, however, is found in the Primates, i.e., monkeys, apes, and man. There can be no doubt that monkeys—even after making all due allowance for their enormous advantage in the possession of hands—display distinctly more intelligence than four-footed Mammals.

Monkeys quickly learn to employ tools as a means to an end—e.g., a stick to secure food which is out of reach. Monkeys also display more initiative and curiosity than other animals; and in these features their behavior approaches that of man. Moreover, the anthropoid apes—which resemble man most closely in the structure of their bodies and especially of their brains—are more "human" in their behavior than the tailed monkeys.

Behavior of Man: Language. An older point of view regarded human behavior as sharply distinct from that of other animals. Man was said to act by "reason," in contrast to the instinctive behavior of other animals; but no such sharp distinction can be drawn. Man displays many simple reflex and instinctive responses, while many of the higher animals show more or less intelligent behavior. On the other hand, many writers, in attempts to minimize the differences between human and other animal behavior, have perpetrated highly exaggerated accounts and utterly uncritical interpretations of the "intelligent" behavior of animals. The truth probably lies in the other direction: i.e., far more of human behavior than is commonly supposed is purely instinctive and automatic. Nevertheless, there is an enormous gap between the achievements of man—at least of civilized man—and those of other animals. The essential clue to this difference seems to lie in one peculiar feature of human behavior: language. Every known race of man has some kind of language; and there is no good evidence that any other animal has.

A word is both a response and a stimulus. On the one hand, a word is a conditioned reflex which may be elicited by a variety of substituted stimuli; and on the other hand, it is a stimulus which has been substituted for many other stimuli. In short, a word is a relatively simple motor act which "sums up" a vast amount of experience. A word is a vehicle of experience; and this distinguishes words from purely instinctive or emotional sounds, which are uttered by many animals. Language consists not merely of words, but of combinations of words. The separate words are, in general, purely imitative, but the word combinations are largely original. Every conditioned reflex involves

an element of originality, in a sense; that is, it represents a new combination of stimuli and responses, so far as the individual animal is concerned. Thus language may be described as a mode of behavior which enormously extends the range of original responses in all mankind.

TEST QUESTIONS

1. Explain how the nerve impulse (a) differs from, and (b) is similar to, the state of excitation in cells generally.
2. Discuss the fatigue susceptibilities of nerve and muscle and relate this problem to the relative rates of oxidative metabolism.
3. Differentiate between the members of each pair of terms:
   a. the absolute and relative refractory periods;
   b. the relative refractory period and the supernormal period;
   c. centralized and decentralized nervous systems;
   d. the peripheral and central parts of the nervous system;
   e. afferent and efferent nerve fibers;
   f. neurons and protoneurons;
   g. a nerve fiber and a neuron;
   h. axons and dendrons.
4. Nerve impulses do not grow weaker as the transmission route becomes longer. Explain this statement, comparing the nerve impulse to a current traversing an electric circuit.
5. Differentiate between the members of each pair of terms:
   a. a reflex arc and a reflex act;
   b. unilateral and bilateral reflexes;
   c. intrasegmental and intersegmental reflexes;
   d. association neurons and other neurons.
6. What are the synapses and why have synapses been studied so intensively?
7. Explain the relationship between the synapses and the law of "forward direction."
8. Discuss briefly each of the following topics in relation to the behavior of an intact animal:
   a. synaptic block;
   b. synaptic resistance;
   c. synaptic summation;

d. synaptic fatigue;
e. facilitation.

9. How does the central nervous system of a vertebrate such as man differ from that of an invertebrate such as the earthworm in regard to:
   a. general structure and position in the body?
   b. relative development of the "higher centers"?
   c. general function?
10. Differentiate between gray matter and white matter:
    a. in general;
    b. in the spinal cord;
    c. in the cerebrum and cerebellum.
11. Differentiate between:
    a. somatic and visceral reflexes;
    b. the cranial and the spinal nerves;
    c. the dorsal and ventral roots of a spinal nerve.
12. Carefully describe the results of each of the following operations:
    a. cutting the dorsal root of one spinal nerve;
    b. cutting the ventral root of a spinal nerve;
    c. a right hemisection of the spinal cord;
    d. cutting the olfactory nerves (cranial nerve, I);
    e. cutting the facial nerves (VII);
    f. cutting the vagus nerves (X).
13. Differentiate between:
    a. the functions of the cerebrum and the cerebellum;
    b. the sensory and motor areas of the cerebral cortex;
    c. sensory and motor tracts;
    d. the pain-temperature tracts and the touch-pressure tracts.
14. How do visceral reflexes differ from somatic reflexes in regard to:
    a. the innervation of the effector organs?
    b. myelination of the motor nerve fibers?
15. Explain the antagonistic action of the sympathetic and parasympathetic nerves, using the heart and the digestive tract to exemplify the discussion.
16. Differentiate between:
    a. lateral and collateral ganglia;
    b. sympathetic and parasympathetic ganglia;
    c. preganglionic and postganglionic fibers.
17. Describe an experiment which demonstrates the existence of:

a. a parasympathetic excitatory substance (acetylcholine);
b. a sympathetic neuro-humor (sympathin).

18. Briefly discuss the chemical theory of synaptic transmission.
19. Distinguish clearly between (a) simple and compound reflexes and (b) conditioned and unconditioned reflexes, citing at least one example in each case.
20. Briefly discuss the relations between:
    a. unconditioned responses and the survival of a species;
    b. facilitation and the establishment of conditioned reflexes;
    c. the development of the cerebral cortex and an animal's capacity to form conditioned reflexes.

FURTHER READINGS

1. *Forced Movements, Tropisms, and Animal Conduct,* by Jacques Loeb; Philadelphia, 1918.
2. *The Integrative Action of the Nervous System,* by C. S. Sherrington; New York, 1926.
3. *Lectures on Conditioned Reflexes,* by J. P. Pavlov; New York, 1928.

PART IV

HEREDITY AND EVOLUTION

CHAPTER 25

HEREDITY

THE DISTINCTIVE *individuality* of each living thing depends not only upon parental heritage, but also upon environmental experience. However, the potency of the environment in shaping the form and function of each individual will be disregarded for the present; and all attention will be focused upon the factors of heredity.

Identifying the Machinery of Hereditary Transmission. Heredity is a direct consequence of the protoplasmic continuity between parent and offspring. All that a parent generally contributes to the offspring is a small sample of its own protoplasm, usually in the form of a single cell.

Excluding asexual modes of reproduction, which will be considered separately, only the gametes establish continuity between parents and offspring; and consequently the mechanism of hereditary transmission must operate across this slender protoplasmic bridge.

The processes of sexual reproduction indicate very clearly that the hereditary potency of the cytoplasm is not nearly as great as that of the nucleus. In a vast majority of organisms, the male gamete contains virtually no cytoplasm as compared

to the large amount present in the egg—and yet the male and female gametes contribute equally to the hereditary qualities of the offspring. This indicates that the machinery of inheritance lies in the nuclei—or more particularly in the chromosomes—of the gamete cells. The chromosomes, in fact, are the only entities which are always passed on in equal quantities from parents to offspring in sexual organisms generally.

Modern genetics began to develop very rapidly in 1910 under the leadership of Thomas Hunt Morgan; and since that time geneticists in all parts of the world have cooperated in establishing the *chromosome theory of heredity.* In fact there now exists a vast amount of experimental evidence which proves conclusively (1) that chromosomes are the essential agencies in the transmission of hereditary traits; (2) that each chromosome is made up, essentially, of a linear series of definitely localized bodies, called *genes;* (3) that each gene is a decisive factor in determining one or more hereditary qualities in every individual organism.

Continuity of the Germ Cells. In multicellular species, some but not all of the cells retain the potentiality of transmitting their chromosomes to the cells of the next generation. These *germ cells* stand in contrast to the *somatic cells,* which cannot perpetuate their chromosomes beyond the lifetime of the individual organism. The somatic cells of an organism are destined to die with the individual; but the germ cells are potentially immortal (Fig. 298). Only the germ cells establish continuity from individual to individual in each successive generation, and *only changes in the germ cells are effective in changing the hereditary destiny of the species.* Accordingly, it is necessary to follow the germ cells, and to determine how these cells transmit their chromosomes to the gametes and to the offspring.

Among sexual organisms, any cell that stands in line of descent of the eggs or sperm is a germ cell. The germ cells include not only the sperm and eggs; they also include the zygote and some of the cells of the developing embryo, even before the gonads become differentiated (Fig. 299). These early *primor-*

dial germ cells eventually come to lie in the gonads—but now they are called by a different name. In the gonads, while they are multiplying by repeated *mitotic* divisions, the germ cells of an animal are called *gonia*, or more specifically—in the testis of

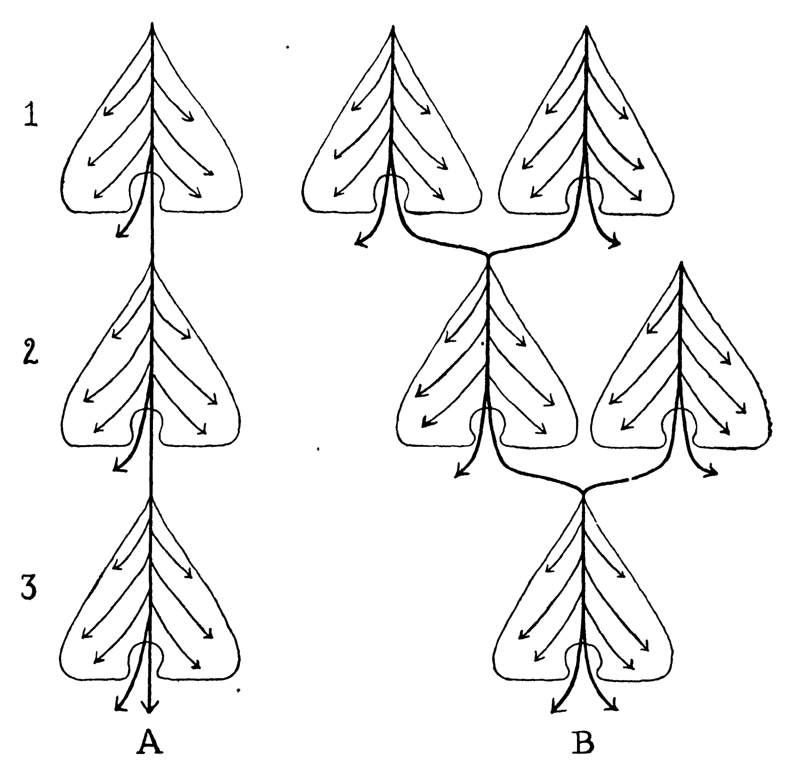


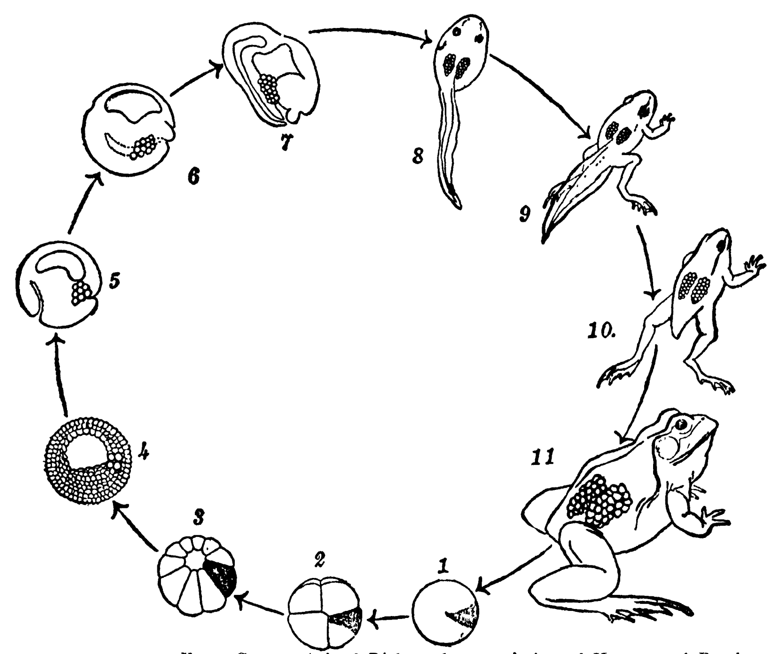
FIG. 298.—Relation between germ plasm and soma: A, in asexual reproduction; B, in bi-parental sexual reproduction. 1, 2, 3, successive generations. Heavy lines represent the germ plasm (protoplasm of the germ cells); light lines represent the cells of the body, or soma.

the male animal the germ cells are called *spermatogonia;* in contrast to the *oögonia* which lie in the ovaries of the female.

Gametogenesis: Maturation of the Gametes. In the gonads of the *adult,* the eggs and sperm begin to undergo *maturation;* and during maturation the chromosomes of the ripening eggs and sperm go through similar stages of development. However, there are certain differences, and this makes it neces-

sary to give a separate description of the maturation of the two kinds of gametes.

A very brief description of the maturation of the sperm was given previously (Chap. 3), but now it is necessary to follow the



From Guyer, *Animal Biology*, by permission of Harper and Brothers

FIG. 299.—Continuity of the germ cells in the life cycle of the frog; 1, the fertile egg—the shaded area becomes cytoplasm of the germ cell; 2, eight-celled stage; 3, thirty-two-celled stage; 4, blastula showing four germ cells; 5-7, successive stages in the development of the gastrula, showing germ cells; 8-10, metamorphosing frogs; 11, mature frog with eggs in ovary ready to be discharged. (After Conklin.)

process more closely. In the testes, when a spermatogonium stops multiplying by mitosis and begins to grow, it is a sign that the *meiotic* divisions are about to occur (Fig. 300). Now each germ cell is called a *primary spermatocyte* and each primary spermatocyte is destined to form *four* sperm (Fig. 300). In fact the growth of the primary spermatocyte proceeds simultaneously with the long prophase of the first meiotic division; and during this growth stage the pairs of chromosomes engage

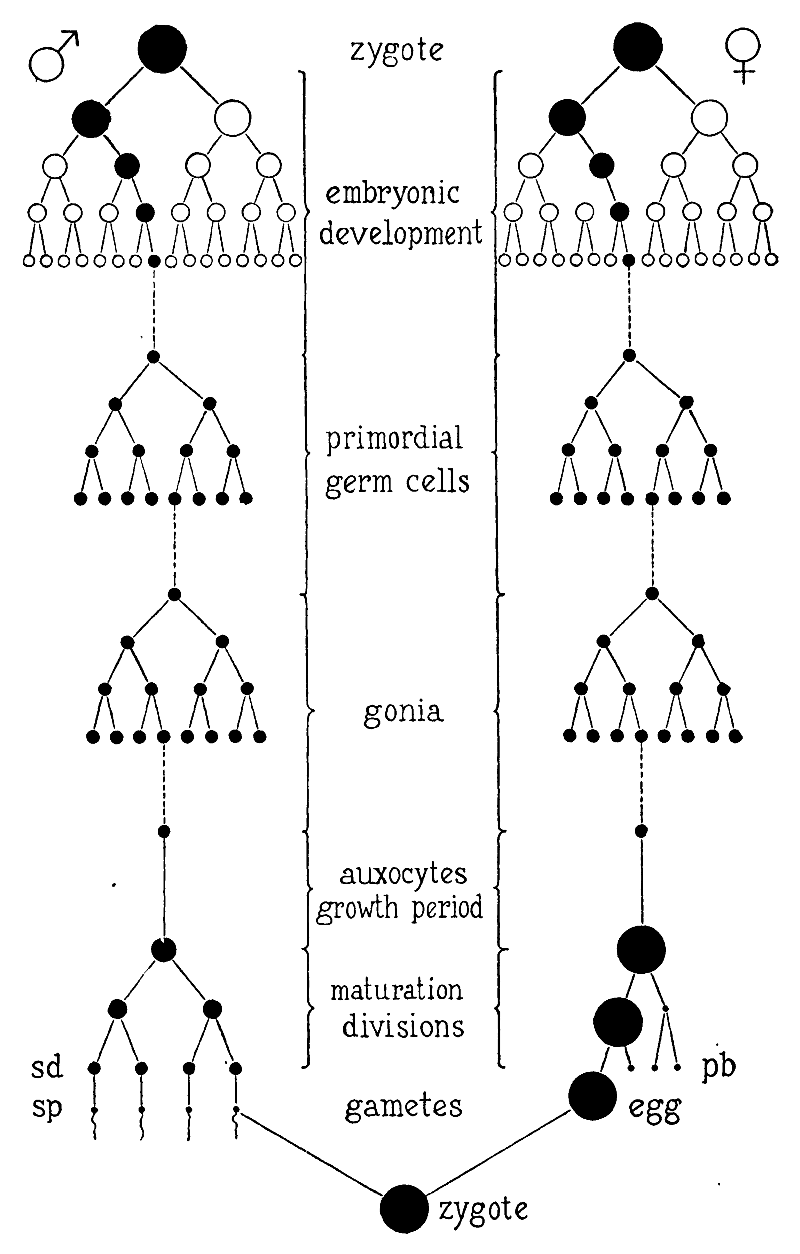


Fig. 300.—History of the germ cells in multicellular animals; germ cells black, somatic cells white. The number of cell divisions is, of course, actually much greater than shown here (except in the maturation period). pb, polar bodies; sd, spermatids; sp, sperms. (Adapted from Wilson.)

themselves in *synapsis* (Fig. 301). After growth and synapsis, the first and second meiotic divisions usually proceed quite rapidly. First the two *secondary spermatocytes* are formed, and

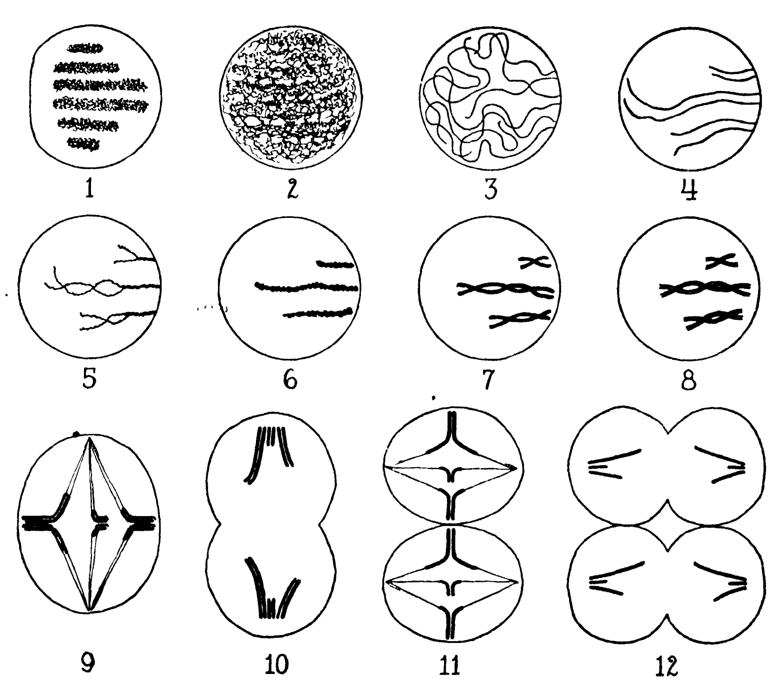


FIG. 301.—Diagram of meiosis. In this diagram the haploid number of chromosomes is three, and these are distinguished from each other by differences in length. 1, telophase of last gonial division, showing the diploid number of chromosomes; 2, intermitotic ("resting") stage of early auxocyte; 3, 4, thin-thread stages, showing diploid number of univalent chromosomes, beginning to pair; 5, 6, synapsis of homologous chromosomes; 7, post-synapsis chromosomes; 8, longitudinal split, formation of the tetrads; 9, 10, first maturation division, dividing each tetrad into two dyads; 11, 12, second maturation division, resulting in four haploid nuclei.

then each secondary spermatocyte divides. This second of the meiotic divisions forms the four *spermatids,* which soon grow tails and become actively motile sperm (Fig. 300).

The diploid nature of the germ cells prior to the meiotic divisions follows from the fact they are derived entirely by mitosis from the original zygote that produced all the cells of the indi-

vidual. But when the meiotic divisions have been completed all the sperm are haploid (Fig. 301). The single haploid set of chromosomes which is carried by the sperm represents the essential contribution of the male parent toward the hereditary constitution of the offspring.

Oögenesis differs from *spermatogenesis* mainly as to the behavior of the cytoplasm during the meiotic divisions. In the case of the ripening egg (Fig. 300), the growth period, during which synapsis occurs, is more pronounced; and due to an accumulation of yolk, the primary oöcyte becomes very much larger than the primary spermatocyte. But more important still is the fact that the two meiotic divisions which follow are highly unequal as to the apportionment of cytoplasm amongst the four resulting daughter cells (Fig. 300). One cell, which is the *ripe* egg, receives virtually all the accumulation of yolk and cytoplasm, whereas the three *polar bodies* receive only an insignificant fraction. Thus the ripe egg, if fertilized, is equipped to develop into an embryo, but the polar bodies are not.

The behavior of the chromosomes during the maturation of the eggs is precisely the same as it is during the maturation of the sperm (Fig. 301). Consequently the net result of oögenesis is the production of four haploid cells; but only one of these can function as the female gamete. When fertilization occurs this ripened egg transmits its haploid set of chromosomes to the nucleus of the zygote, and this is the essential donation of the female parent to the genetic constitution of the offspring.

Free Assortment of Chromosomes During Meiosis. As was emphasized previously (p. 58), the fact that only *one* division of the chromosomes occurs during the *two* meiotic divisions, results inevitably in a reduction of the chromosome number of the gametes as compared to the other cells of the animal. At one point or another during meiosis the members of each homologous pair of chromosomes become separated from each other, and each mature gamete comes to possess just a single member of each chromosome pair. It is, however, entirely a matter of chance as to which member of any chromosome pair

goes to a particular gamete, and the various possibilities show up with equal frequency.

Take for example the sperm formed from spermatogonia possessing two pairs of chromosomes, namely:

Aa
Bb

During spermatogenesis, this type of germ cell can produce only four *kinds* of sperm, namely:

A	*a*	*A*	*a*
B	*b*	*b*	*B*

These sperm will be produced in equal numbers, since each chromosome has the same chance of finding its way into any of the gametes. Similarly, oögonia with two pairs of chromosomes can produce only four kinds of eggs, with corresponding combinations of chromosomes.

But if the spermatogonia (or oögonia) possess *three* pairs of chromosomes, namely:

Aa
Bb
Cc

The following eight kinds of gametes will be produced in equal numbers:

A	*a*	*A*	*a*	*A*	*a*	*A*	*a*
B	*b*	*B*	*b*	*b*	*B*	*b*	*B*
C	*c*	*c*	*C*	*C*	*c*	*c*	*C*

When an individual animal produces eggs or sperm, therefore, the several chromosomes which were received from its maternal and paternal parents are free to assort themselves at random in the next generation of gametes, except that *one member of every pair of chromosomes is always represented in every gamete which is produced.*

In *plants,* the origin of the haploid gametes is less direct than in animals, but essentially the same system of transmitting

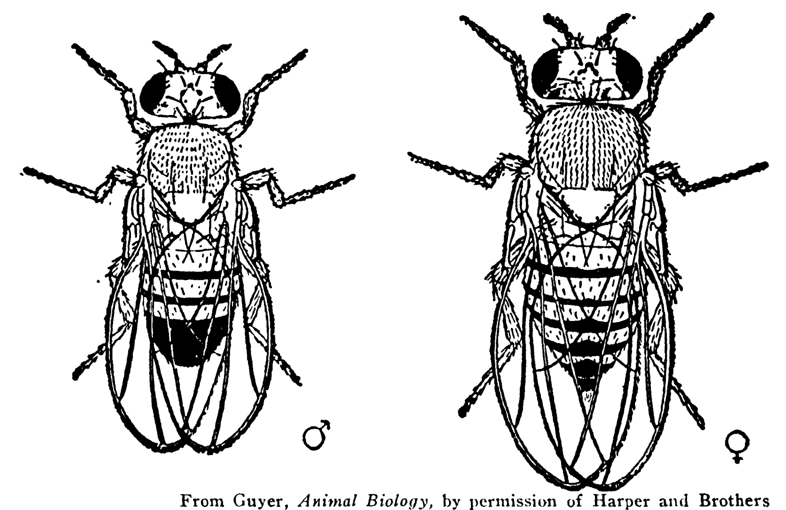
chromosomes from parent to offspring is at work. Among plants fertilization does not take place immediately after meiosis. Instead, a whole haploid generation, the gametophyte generation, intervenes—and the diploid condition is not restored until the gametes unite, forming a zygote and initiating the sporophyte generation. This peculiarity, however, does not fundamentally alter the processes of heredity, which are essentially similar in all sexual organisms.

Breeding Experiments. The first accurately controlled and thoroughly documented breeding experiments were published in 1866 by Gregor Mendel. This Austrian monk worked with garden peas; and by strictly controlling the pollination of his plants, Mendel discovered a well-defined pattern which governed the transmission of a number of hereditary features, such as color, height, hardiness, etc., throughout many successive generations. The importance of Mendel's experiments was not recognized, however, until about 1900. By this time much more had been learned about chromosomes; and now biologists were ready to recognize the crucial role of the chromosomes in the fulfillment of the Mendel laws.

Genetic experiments presuppose a very accurate knowledge of the stocks which are to be crossed. The aim is to study the transmission of *single hereditary differences*, either separately or in combination, by crossing two stocks and determining the numerical distribution of the hereditary peculiarities among the offspring. But unless the number of differences is relatively small, an analysis of the results becomes very complex. Consequently it was most fortunate that Mendel began his work with a self-pollinating species of plant, in which the original stocks possessed a high degree of genetic homogeneity.

Modern genetics owes a great debt to a diminutive animal, *Drosophila melanogaster*, commonly called the fruit-fly (Fig. 302). Morgan and his students found that Drosophila is ideally suited for experimental breeding. At the age of 12 days these little flies begin to breed; and by the end of three weeks a single female can produce 300 offspring. Accordingly, within 3 years

it is possible to study more than 60 generations of Drosophila—or about as many generations as have accrued to mankind during all the Christian era. Furthermore, many specimens of Drosophila can be housed in a single milk bottle; and the food of Drosophila, which is mainly fermenting bananas, is a negligible problem of laboratory expense. Because of these advantages, ex-



From Guyer, *Animal Biology*, by permission of Harper and Brothers

FIG. 302.—Male and female fruit fly, Drosophila melanogaster. (After Morgan.)

periments on Drosophila have pioneered practically all advances in modern genetics. However, the laws of heredity, as worked out in Drosophila and other lower forms, have proved to be generally applicable to man and all other higher organisms.

Mendelian Inheritance: Segregation. The *law of segregation* deals with the transmission of a *single hereditary difference* from parent to offspring in successive generations. Mendel worked out the law of segregation by studying the inheritance of flower color; but our first example will be chosen from a special breed of chicken, the *Andalusian fowl.*

Two stocks of Andalusians have been cultivated for many years: one white and the other black. If these stocks are *inbred,* white to white, or black to black, no change of feather color ever

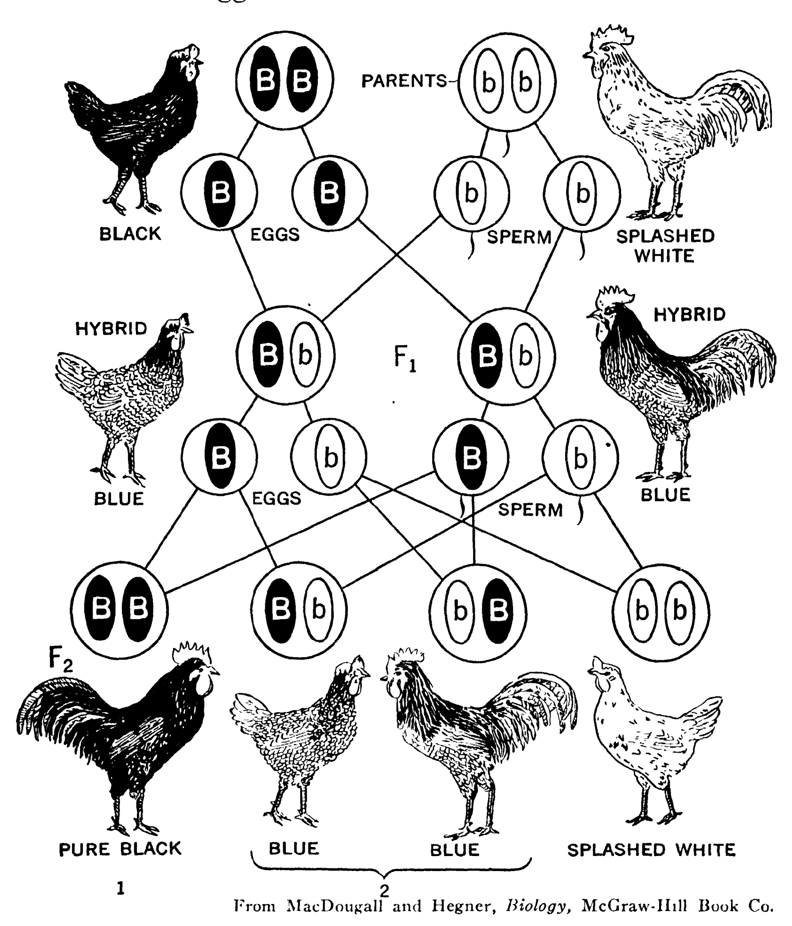
appears: white crossings never yield anything but white offspring, and black crossings yield only blacks.

If a white hen (or rooster) is crossed to a black mate, *all the offspring* display an intermediate pigmentation—a sort of gray-blue. But if any two blue individuals are *inbred:* 25 per cent of the offspring are pure white, like the one grandparent; 50 per cent are blue, like the immediate parents; and 25 per cent are pure black, like the other grandparent. Or, to state these results more technically—when the P_1 (first parental) generation of Andalusians are pure white and black respectively, all individuals of the F_1 (first filial) generation will be blue; but the F_2 (second filial) generation, obtained by inbreeding the F_1, consists of white, blue and black fowl in a ratio of 1 : 2 : 1 (Fig. 303). Furthermore, by inbreeding the different kinds of F_2 individuals the same results are obtained: whites always give only whites; blacks give only blacks; a white and black yield all blues; and a blue crossed with a blue give a 1 : 2 : 1 ratio of whites, blues and blacks.

Provided the F_1 *hybrids* are clearly distinguishable from both of the pure line parents, similar results are always obtained in any *one factor cross*, in which the mated individuals possess just a single hereditary difference.

The results of this and all other similar breeding experiments can be explained by a very simple hypothesis, which has been substantiated by many lines of evidence. The feather color differences are due to a single pair of genes which are localized in a particular pair of homologous chromosomes. Black fowls, when inbred, never give rise to any white offspring, and consequently it is certain that the black stock has *both* of the feather-color genes of the same kind (B) which fosters the production of black pigment (Fig. 303). Similarly inbred white fowls always produce only white progeny, so that both of the feather color genes of this stock must be of the same kind (b) which is not a pigment producer (Fig. 303). Or to phrase these ideas more technically, the black Andalusian is said to be homozygous (BB) with reference to the "black gene"; whereas the white fowl is homozygous (bb) as to the "white gene." Furthermore,

this genic condition obtains in all the diploid cells of the organism, since all the cells have been derived by mitosis from the same fertilized egg.



From MacDougall and Hegner, *Biology*, McGraw-Hill Book Co.

FIG. 303.—Cross between a splashed white and black Andalusian fowl. The hybrid is popularly called a "blue" Andalusian fowl. (Jane Wyatt.)

Granting these assumptions, the results of the breeding experiments follow automatically from the known events of gametogenesis and fertilization—as may be seen in Fig. 303. As to feather color genes, each of the P_1 fowls can produce only one kind of egg, or sperm, depending on the sex. Consequently all

F_1 individuals must be alike; all are *heterozygous* (*Bb*) as to the feather color genes. But when the F_1 hybrids form gametes, each fowl produces *two kinds of gametes* in equal numbers. Half the eggs and half the sperm must carry the *B*-gene, and half must carry the *b*-gene. Consequently, depending entirely on the chance union of the gametes, the F_2 offspring must be homozygous black (*BB*), heterozygous (*Bb*) blue, and homozygous white (*bb*) in a ratio of 1 : 2 : 1 as is indicated in the following *Punnett Square:*

F_1 eggs / F_1 sperms	*B*	*b*	
B	*BB* black	*Bb* blue	F_2 zygotes
b	*Bb* blue	*bb* white	

All other matings among Andalusians can be explained by the same mechanism. A blue hen mated to a black cock produces blues and blacks on a 1 : 1 basis; and similarly a cross between a blue and a white fowl gives blues and whites in a 1 : 1 ratio (Fig. 304). In fact the chromosome hypothesis has been validated by experiments on a countless number of unit hereditary differences, taken singly and in combination, in practically every kind of plant and animal.

The results so far indicate that a parent transmits hereditary qualities to the offspring through the agency of *discrete material masses*, called *genes*, which are borne in the chromosomes of the germ cells. All the diploid cells of the organism are equipped with at least two genes which influence the development of any one characteristic. In exerting its effect, each gene maintains a discrete individuality. Its effects upon the organism may be blended with the effects of other genes, but the gene itself *is not changed* by this association. During meiosis in the succeeding generation, the members of each pair of genes become *segregated* into separate gametes, so that each gamete can transmit only one of any given pair of genes.

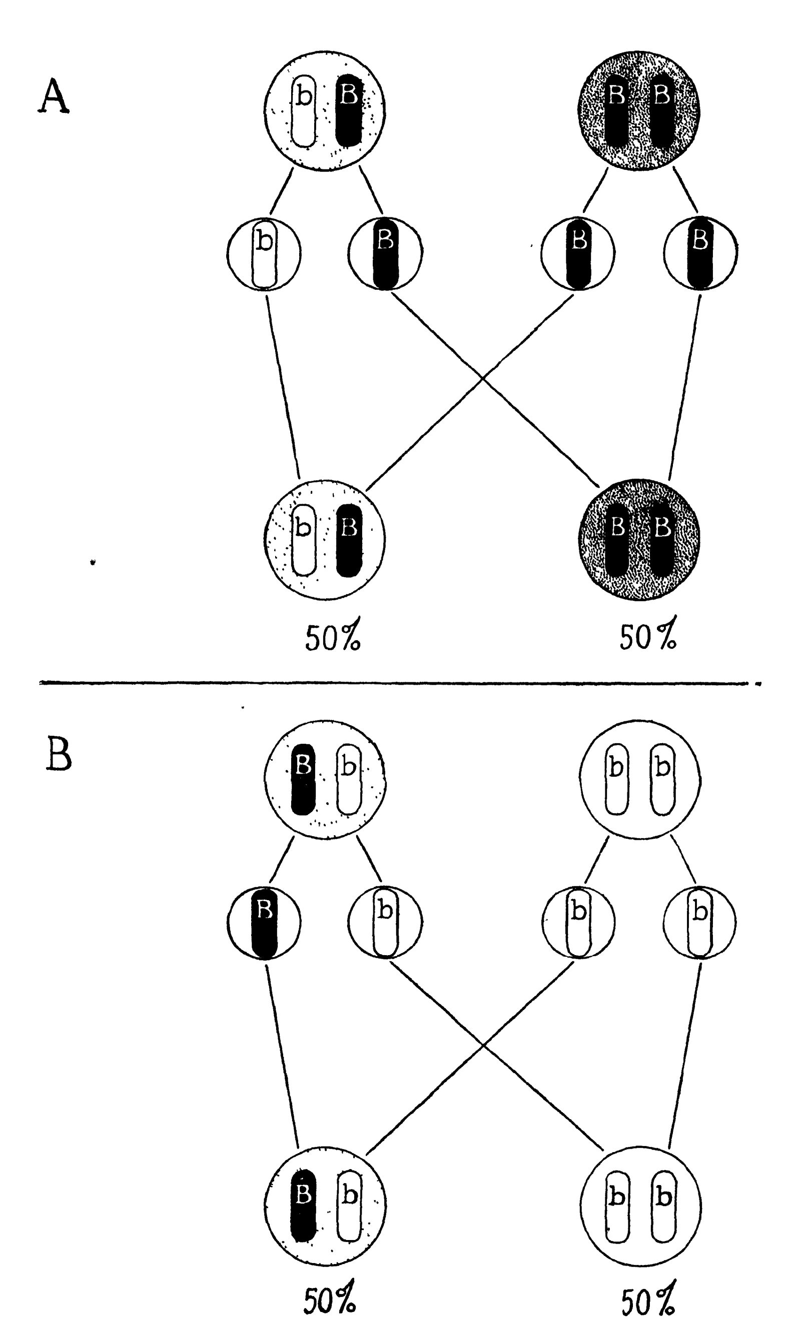


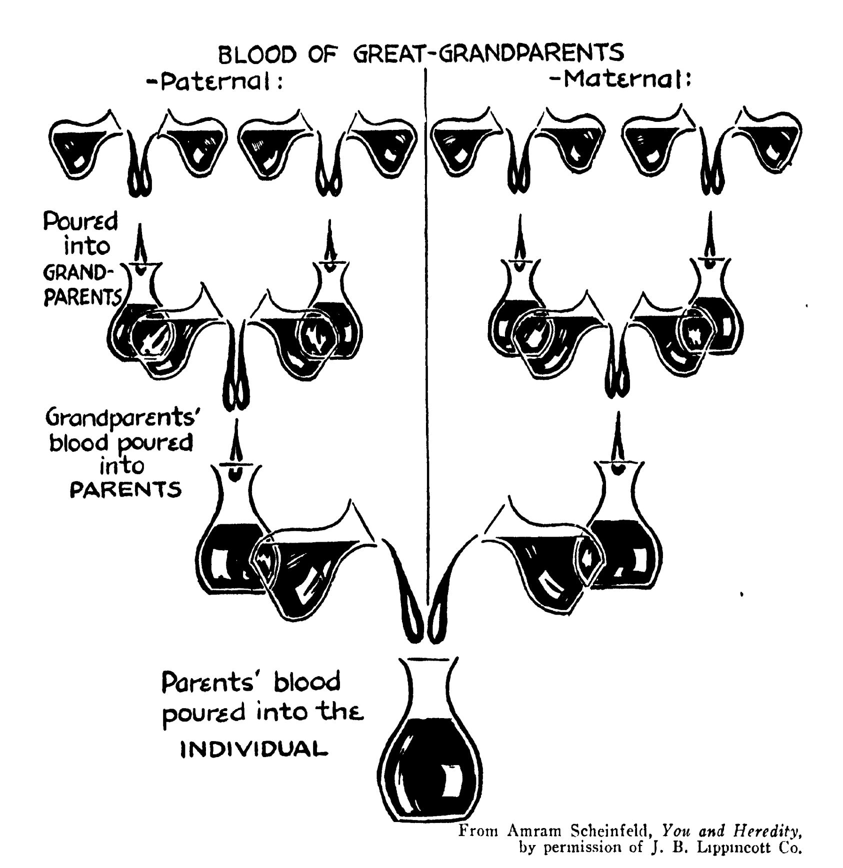
FIG. 304.—A, cross of blue and black Andalusians; B, cross of blue and white.

All of the foregoing ideas are implicit in the work of Mendel, except that Mendel referred to "factors" rather than genes; and Mendel did not realize that the factors are localized in the chromosomes. The central and pre-eminently important concept of Mendelian inheritance is the realization that the genes are *stable self-perpetuating units* which are transmitted throughout many generations. This means that the characteristics of a stock are not lost by dilution, but tend to appear without alteration generation after generation. Heredity is, indeed, more a matter of "shuffling" (not mixing) the genes during the processes of meiosis and fertilization. Or, in other words, heredity is *particulate*—a process of transmitting discrete particles, which are the genes. This is in sharp contrast to many older concepts of heredity. These older views considered heredity to depend upon a sort of blending process in which inevitably the characteristics of a stock would be further and further attenuated with each succeeding generation of out-breeding (Fig. 305).

Allelic Genes. Each gene occupies a *specific locus* in a *specific chromosome* of the species; and all genes occupying this locus in a given pair of chromosomes are said to be *allelic* to each other. Among Andalusians, for example, the "black" gene (*B*) is the allele of the "white" gene (*b*), since these genes occupy corresponding loci in the same chromosome pair. In other words, just as the chromosomes in the diploid cells of the organism occur in *homologous pairs,* so the genes are present as *allelic pairs;* and if one of the alleles of a certain pair has been derived from one of the parents, the other inevitably was derived from the opposite parent.

Dominant Genes. The case of the Andalusian fowl was taken as a first example in Mendelian inheritance because neither of the allelic genes determining feather color obscures the effects of the other. In many cases, however, one member of an allelic pair may totally hide the effects of the other. Such *dominance* is shown in the following experiment, which deals with the inheritance of *seed-color* in garden peas, a material used by Mendel in his original studies.

Two stocks of garden pea have been cultivated: one with yellow seeds, the other with green. Both stocks breed true when self-pollinated; i.e., no greens are obtained from the yellows,



From Amram Scheinfeld, *You and Heredity*, by permission of J. B. Lippincott Co.

FIG. 305.—Heredity is not a blending process. Genes are not subject to dilution or contamination by other genes.

and vice versa. When such stocks are cross-pollinated, in either direction, all the F_1 seeds display a yellow color. Proceeding to the F_2 generation, obtained by self-pollinating the plants grown from the yellow seeds, 75 per cent of the F_2 seeds are yellow and 25 per cent are green.

Figure 306 shows that this case is similar to the experiment with the Andalusians, except that one of the gene-pair deter-

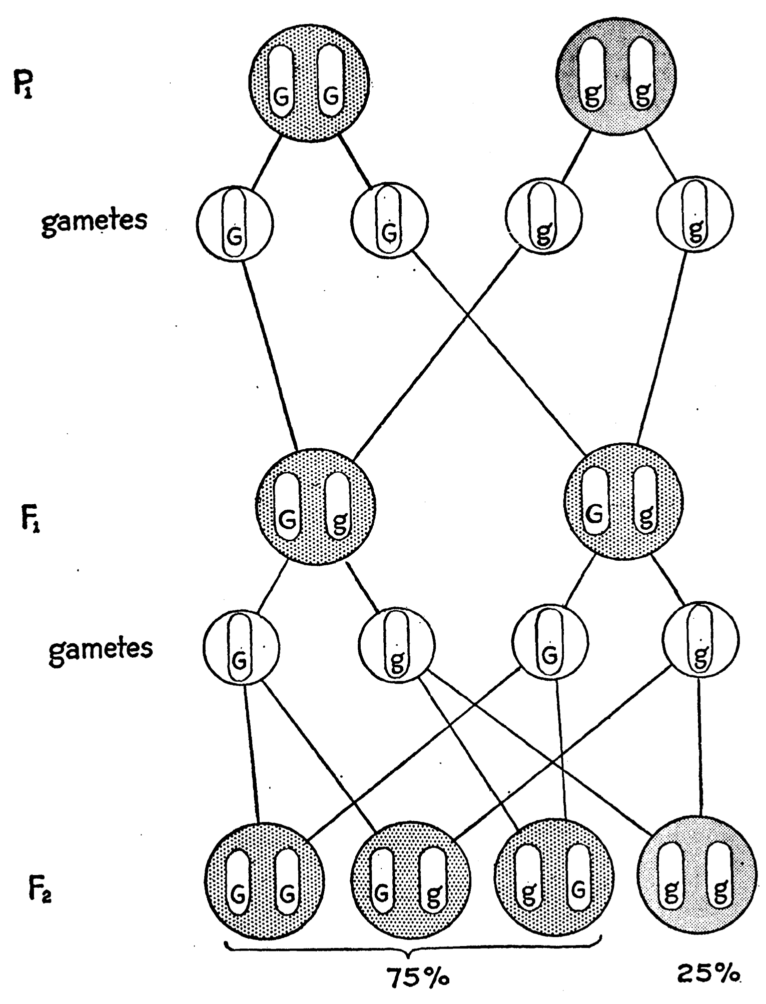


FIG. 306.—Cross between yellow- (GG) and green- (gg) seeded garden peas. Due to the dominance of the "yellow gene" (G), heterozygous (Gg) seeds display the same appearance as homozygous (GG) ones.

mining seed color *being dominant*, supresses the effects of the other (*recessive*) gene. The P_1 green-colored seeds must have been homozygous (having the two genes of the allelic pair iden-

tical) as to the "green gene" (*g*) and the yellow-seeded stock must likewise have been homozygous for the "yellow gene" (*G*); otherwise neither of these stocks would breed completely true with successive self-pollinations. Consequently only one kind of gamete is produced by each of the P_1 parents, and all of the F_1 hybrids are inevitably alike (Fig. 306). Due to the dominance of *G*-gene, however, all the F_1 seeds display a yellow color. But during meiosis, when segregation occurs, the F_1 plants form two kinds of spores, and subsequently, the same two kinds of gametes (Fig. 306). Consequently when the F_1 eggs and sperm combine at random, the F_2 seeds must come out "yellow" and "green" in a ratio of 3 : 1, as is shown by the following Punnett Square:

F_1 eggs / F_1 sperm	*G*	*g*	
G	*GG* yellow	*Gg* yellow	F_2 zygotes
g	*Gg* yellow	*gg* green	

Genotype vs. Phenotype. Although all *look* alike, not all of the yellow-colored F_2 seeds *are* identical as to their genetic constitution (Fig. 306). All the F_2 yellow seeds belong to the same *phenotype* (a type of organism judged on the basis of its appearance), but two different *genotypes* (types based on the genic constitution) are represented. Some of the yellow F_2 seeds (Fig. 306) are homozygous (*GG*) but others are (*Gg*), or *heterozygous* (i.e., the two genes of an allelic pair are not the same) as to their genic nature.

A dominant-recessive relation between allelic genes is the general rule rather than the exception among animals and plants, although frequently the dominance is not altogether complete. When the dominance is complete, as in the present case, the presence of a single recessive gene cannot be determined by the appearance of its possessor, but onlv by the breed-

ing potentialities. If the recessive gene is present, the corresponding trait will turn up in a subsequent generation, as soon as the homozygous condition happens to be established at the conception of some future individual. In other words, although organisms of the same phenotype may look alike, they do not *breed* alike, unless they also belong to the same genotype.

In comparing the experiments so far, garden peas give exactly the same results as Andalusians, if one determines the F_2 ratios in terms of genotypes rather than in terms of the phenotypes. The ratio is 1 : 2 : 1, with reference to genotypes (*BB*), (*Bb*), and (*bb*) in the Andalusian; and also 1 : 2 : 1 for genotype (*GG*), (*Gg*) and (*gg*) in the garden pea (Figs. 303 and 306). The different phenotype ratios—1 : 2 : 1 for Andalusians, and 3 : 1 for the peas—merely indicate that among Andalusians, each different phenotype represents a distinct genotype; whereas among garden peas, the yellow phenotype, due to dominance, consists of two genotypes.

Back-Crossing to Determine Genotype. The simplest method of determining the genotypes present in a given phenotype is to *back-cross* the unknown F_2 individuals. This procedure involves mating the unknown to its homozygous *recessive* grandparent (Fig. 307). The advantage of the back-cross is that it gives very simple results, which are easy to analyze—as may be seen in the following experiment.

Any yellow-seeded F_2 pea (Fig. 306), which may be either homozygous (*GG*) or heterozygous (*Gg*), is back-crossed to a green-seeded (*gg*) plant and the offspring are examined. If the unknown is of the (*GG*) genotype, all the offspring will be yellow seeds, as is shown in Fig. 306 (the F_1 generation). But if the unknown is genotype (*Gg*), only half the offspring will be yellow and the other half will be green, as is shown in Fig. 307. Thus the back-cross gives a simple 1 : 1 ratio, if one deals with a heterozygous individual, as compared to the single product obtained from a homozygous specimen.

Dominance does not in any way alter the mechanics of transmission of a gene, but merely changes the potency of the gene

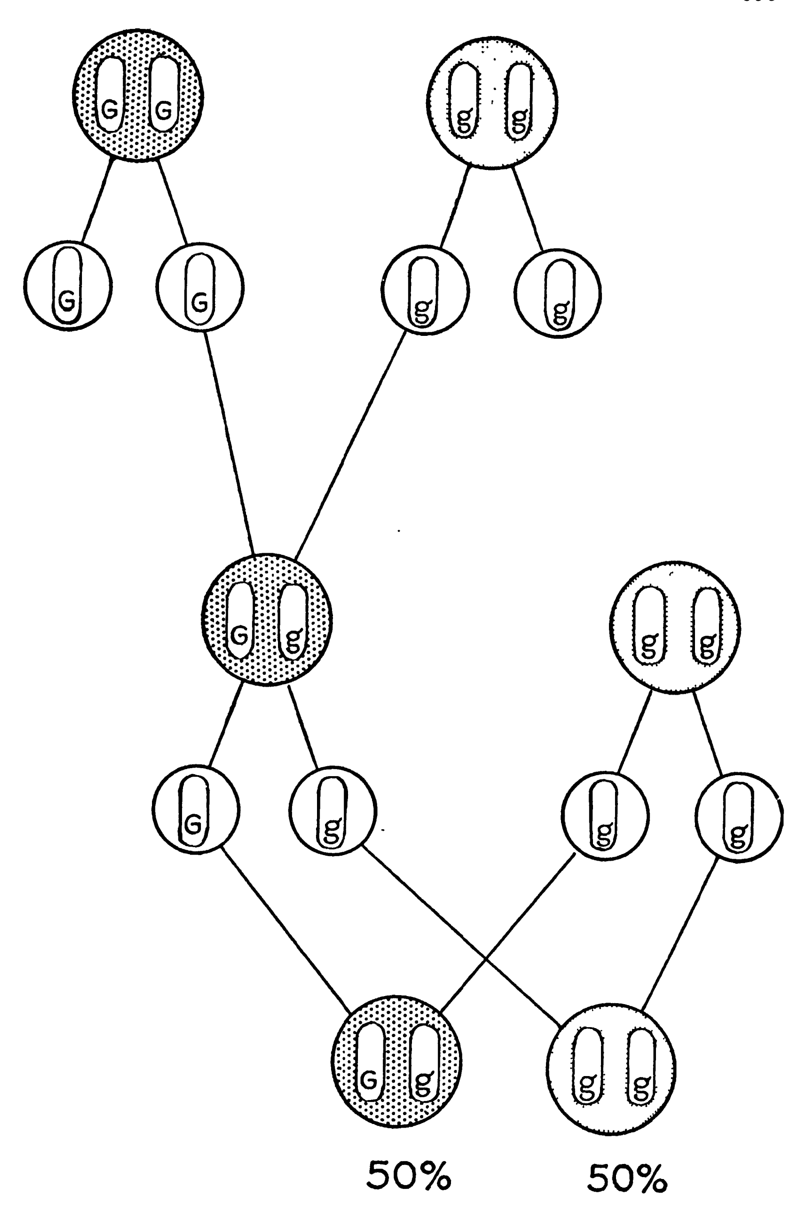
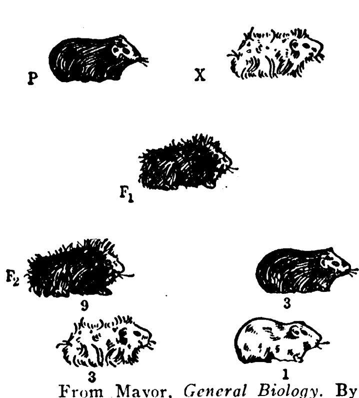


FIG. 307.—The back-cross, i.e., mating an unknown individual to an individual which is homozygous-recessive for the genes in question. If the unknown is homozygous for the dominant gene (top) only one kind of offspring is obtained; if heterozygous, two kinds are produced.

as a determinant of developmental processes in the organism. But how the genes, which are transmitted via the zygote to all the cells of the body, manage to produce their profound effects upon developmental processes, is a problem which will be discussed later (p. 674).

Independent Assortment: Two or More Gene Pairs in Separate Chromosome Pairs. During gametogenesis several or many pairs of chromosomes are "dealt out" simultaneously to the maturing gametes; and consequently it is impossible to predict the exact hereditary constitution of any given egg or sperm. But two or three gene pairs, even if *localized in different pairs of chromosomes*, can be followed. This permits the hereditary results to be predicted very accurately, as in the following experiment on the inheritance of *hair characteristics in guinea pigs.*



From Mavor, *General Biology*. By permission of The Macmillan Co.

FIG. 308.—Cross between a black-smooth and a white-rough guinea pig. The F1 individuals are black-rough; and when inbred these produce four kinds of offspring in the proportions: 9 black-rough, 3 black-smooth, 3 white-rough, and 1 white-smooth. (After Castle.)

The experiment starts with two well-known laboratory stocks of the guinea pig. One stock with *black, smooth hair* (Fig. 308) has been inbred for many generations without any change in the color and texture of the coat; and the same is true of the other stock, which has *white* hair and a *rough* coat. When crossed these stocks produce nothing but *black-rough* individuals in the F_1 generation. But when inbred the F_1 pigs give F_2 offspring which are black-rough, black-smooth, white-rough and white-smooth, respectively, in a ratio of 9 : 3 : 3 : 1.

On the basis of the known history, the genotype of the P_1 black-smooth stock must be (*WW ss*) i.e., homozygous for both

the "black gene" (*W*) and for the "smooth gene" (*s*); and the genotype of the white-rough pigs must be (*ww SS*)—i.e., homozygous for both the white (*w*) and rough (*S*) genes (Fig. 309).

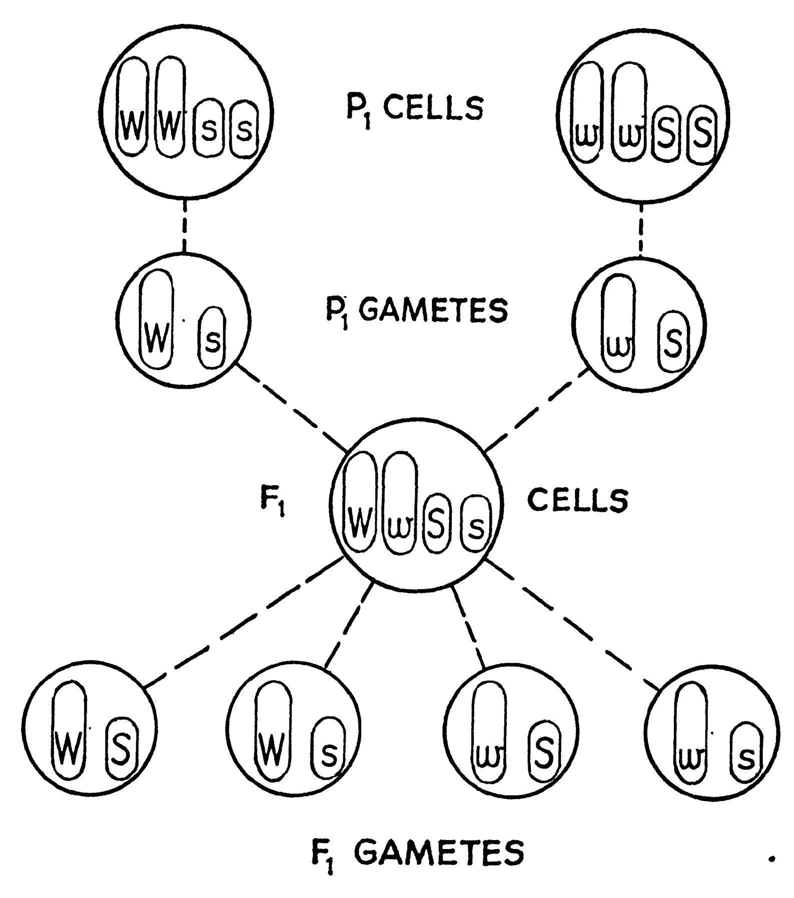


FIG. 309.—The P_1 and F_1 gametes of a "two-factor cross" involving hair-color and hair-length in guinea pigs.

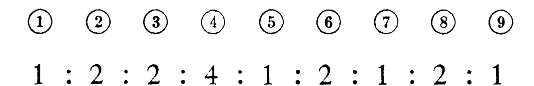
Consequently each P_1 stock produces only one kind of gamete, and all the F_1 pigs must be alike (Fig. 309). But the F_1 hybrids produce four kinds of eggs, and a similar four kinds of sperm (Fig. 309). Consequently when these gametes unite to form the F_2 generation, the following combinations are possible:

F_1 eggs	*W* *S*	*W* *s*	*w* *S*	*w* *s*	
F_1 sperm *W* *S*	*WW* *SS* ① black-rough	*WW* *Ss* ② black-rough	*Ww* *SS* ③ black-rough	*Ww* *Ss* ④ black-rough	F_2 zygotes
W *s*	*WW* *Ss* ② black-rough	*WW* *ss* ⑤ black-smooth	*Ww* *Ss* ④ black-rough	*Ww* *ss* ⑥ black-smooth	
w *S*	*Ww* *SS* ③ black-rough	*Ww* *Ss* ④ black-rough	*ww* *SS* ⑦ white-rough	*ww* *Ss* ⑧ white-rough	
w *s*	*Ww* *Ss* ④ black-rough	*Ww* *ss* ⑥ black-smooth	*ww* *Ss* ⑧ white-rough	*ww* *ss* ⑨ white-smooth	

These combinations account for the phenotype ratio in the F_2 generation, namely:

black-rough	black-smooth	white-rough	white-smooth
9 :	3 :	3 :	1

and also for the ratio of the *nine* genotypes (which are numbered in the Punnett Square):



The random combinations of the F_1 eggs and sperm, as indicated by the Punnett Square, show that four different genotypes, ①, ②, ③ and ④, are represented in the black-rough phenotype; and this is borne out by back-crossing experiments. Thus, if the unknown is genotype ④, the offspring of the back-cross will show a 1 : 1 : 1 : 1 ratio of black-rough, black-smooth, white-rough and white-smooth, as may be seen in the following chart:

Gametes produced by genotype ④ Ww Ss		W S	W s	w S	w s
All gametes of a "double" recessive pig		w s	w s	w s	w s
Offspring of the back-cross	genotypes	Ww Ss	Ww ss	ww Ss	ww ss
	phenotypes	black-rough	black-smooth	white-rough	white-smooth
		1 :	1 :	1 :	1

Similarly genotypes ①, ② and ③ may be determined, if the back-cross yields, respectively, (1) nothing but black-rough offspring; (2) half and half black-rough and black-smooth; or (3) half and half black-rough and white-rough (as may be worked out by the student).

The complete independence of each of the two gene pairs, during the inheritance of hair color and hair texture in guinea pigs, can also be emphasized from another viewpoint. By dissociating the color and texture characteristics the F_2 offspring may be classified as follows:

	rough	smooth	
black	9	3	$\frac{12}{4} = 3:1$
white	3	1	
	12 :	4	

This shows that the 9 : 3 : 3 : 1 ratio of the F_2 generation is obtained merely by superimposing two 3 : 1 ratios. As to color the ratio is 12 blacks to 4 whites; and as to texture the ratio is 12 roughs to 4 smooths. In other words, the guinea pig experiment is just like the case of the garden pea, except that two pairs of genes (instead of one pair) are being transmitted to the offspring, each independently of the other.

In the organism many allelic pairs of genes are simultaneously undergoing *independent assortment* as they are transmitted from generation to generation, although only gene pairs

which are localized in separate pairs of chromosomes, are able to assort independently. In the case of an organism which is heterozygous for *three* pairs of genes, e.g., *Aa, Bb* and *Cc,* eight kinds of gametes

A	*a*	*A*	*a*	*A*	*a*	*A*	*a*
B	*b*	*B*	*b*	*b*	*B*	*b*	*B*
C	*c*	*c*	*C*	*C*	*c*	*c*	*C*

will be formed, providing the allelic genes have loci in *different* chromosomes. Or, to generalize completely, a heterozygous individual will form 2^n classes of gametes in equal numbers, when n is the number of heterozygous allelic genes with loci in different chromosomes.

Mendel's Laws. The experiments which have been presented up to this point exemplify the first two laws of genetics. These are called Mendel's laws, although Mendel had little knowledge about chromosomes and phrased the laws in different terms.

1. *Law of segregation: the genes of every allelic pair are always segregated into separate gametes, each gene remaining completely uncontaminated by the other.*
2. *Law of independent assortment: provided the gene-pairs have loci in different chromosomes, they are assorted among the gametes each independently of the others.*

Linkage (Dependent Assortment). The number of pairs of allelic genes that assort independently cannot be greater than the number of *pairs* of homologous chromosomes of the species (Table XXII), although the total number of genes in any organism is always greater than the number of chromosomes. Each chromosome provides loci for many genes, and the genes of each chromosome tend to be *linked* together during their hereditary transmission.

Drosophila melanogaster provides excellent material for the study of linkage, because this species has only four pairs of chromosomes (Fig. 310). Thus the several hundred genes which

TABLE XXII

CHROMOSOME NUMBERS OF SOME FAMILIAR ORGANISMS *

Common Name	*Species*	*Diploid Number of Chromosomes*
Hydra.	Hydra fusca	12
Pinworm	Parascaris equorum	2
Fruit-fly.	Drosophila melanogaster	8
Dogfish	Scyllium canicula	24
Bullfrog....	Rana catesbiana	26
Dog	Canis familiaris	22
Man...........	Homo sapiens	48
Spirogyra........	Spyrogyra neglecta	24
A liverwort......	Riccia lutescens	8
A moss	Bryum capillare	20
A fern	Pteris aquilina	64
Corn.... . .	Zea mays	20

Selected from Wilson, *The Cell.*

have been identified in the fruit-fly, all fall into four linkage groups, which correspond to the four chromosomes.

Linkage can be demonstrated by following the transmission of two or more gene pairs having loci in the *same* pair of chromosomes. In Drosophila this specification is met by two pairs of genes which determine the *body color* and *wing length* of the flies.

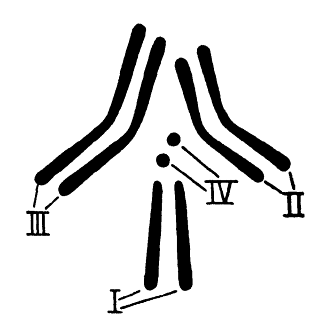


FIG. 310.—Diploid chromosomes of Drosophila melanogaster (female). I, II, III and IV indicate the chromosomes which are mapped in Fig. 315.

In crossing one stock of fly, which self-breeds true for black body and vestigial (reduced) wing, with another true-breeding stock having gray body and large wings, the F_1 individuals are found to have gray bodies and long wings (Fig. 311). Accordingly, the gray (B) gene dominates black (b) and the normal long wing gene (V) is dominant to

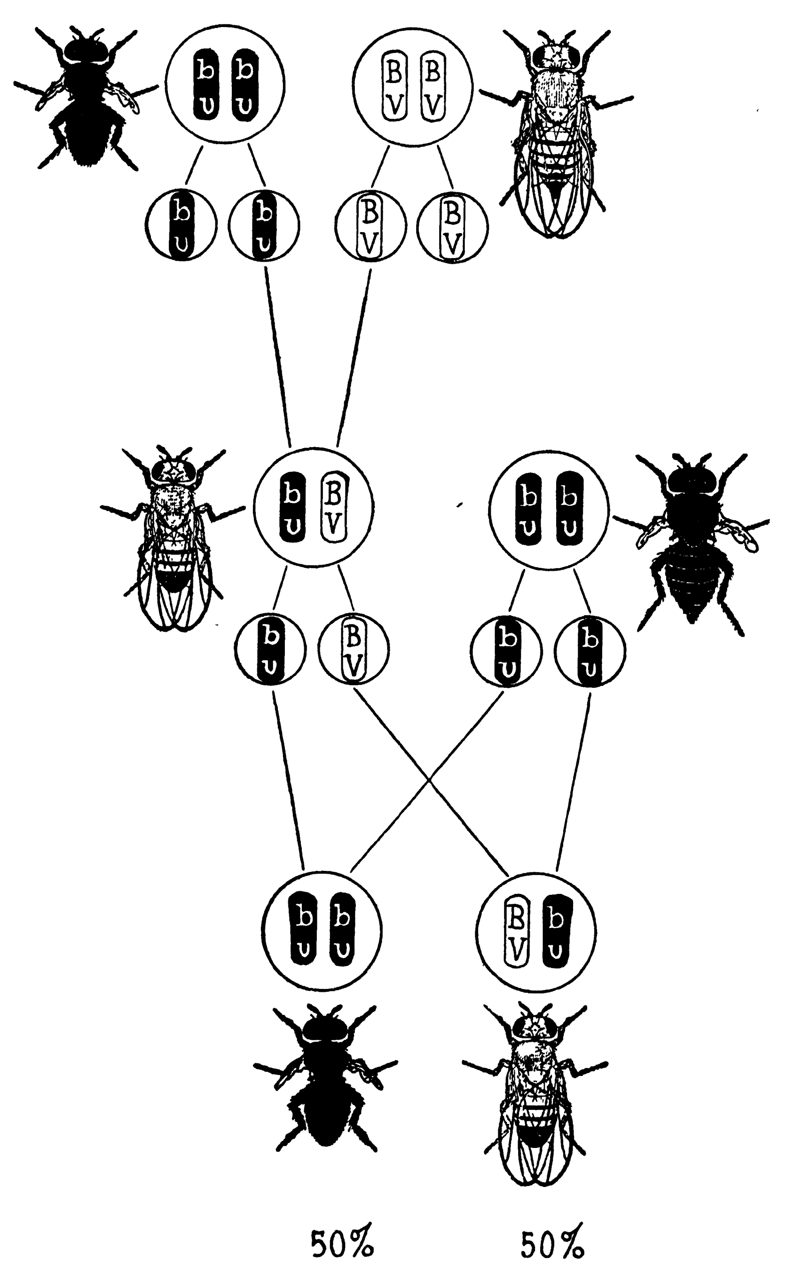


FIG. 311.—Complete linkage: *F*1 male, from cross of black-vestigial and gray-long, back-crossed to black-vestigial female. (Adapted from Morgan.)

the vestigial (v); also both of the P_1 flies are homozygous as to both allelic pairs (Fig. 311). Thus when an F_1 hybrid *male* is *back-crossed* to the double recessive *female*, instead of getting four kinds of offspring such as would be obtained if the genes assorted independently, only two kinds of flies are obtained (Fig. 311). Fifty per cent of the back-cross offspring have black bodies and short wings, and the other fifty per cent have gray bodies and long wings. In other words, the black body and short wing, and the gray body and long wing, are *linked* as to their inheritance, since both of these gene pairs have loci in the same pair of chromosomes.

Incomplete Linkage: Crossing Over. The foregoing case is called complete linkage because the two gene-pairs in the one pair of chromosomes are always inherited together. But complete linkage is a rare phenomenon; i.e., complete linkage occurs only in the *male* Drosophila and very few other known organisms. A back-cross between a *female* F_1 hybrid and a double recessive male gives very different results, in that the offspring are of four types: gray-vestigial, gray-long, black-long and black-vestigial; but these offspring are *not* produced in *equal* numbers (Fig. 312). In fact the results of such a cross cannot be stated as a simple ratio, but only on the following *percentage* basis:

gray-long	41%	82%
black-vestigial	41%	
gray-vestigial	9%	18%
black-long	9%	

In all cases of incomplete linkage, the *original* combinations of characters—those possessed by the P_1 parents—are found in a majority of the offspring: but *new* combinations occur in a minority of the progeny. Moreover, the two majority classes are always equal to each other—as is also true of the minority classes.

To explain these results, attention must be focused upon the F_1 *female* hybrid. This hybrid received chromosomes $\left|\begin{matrix} b \\ v \end{matrix}\right.$ and $\left|\begin{matrix} B \\ V \end{matrix}\right.$

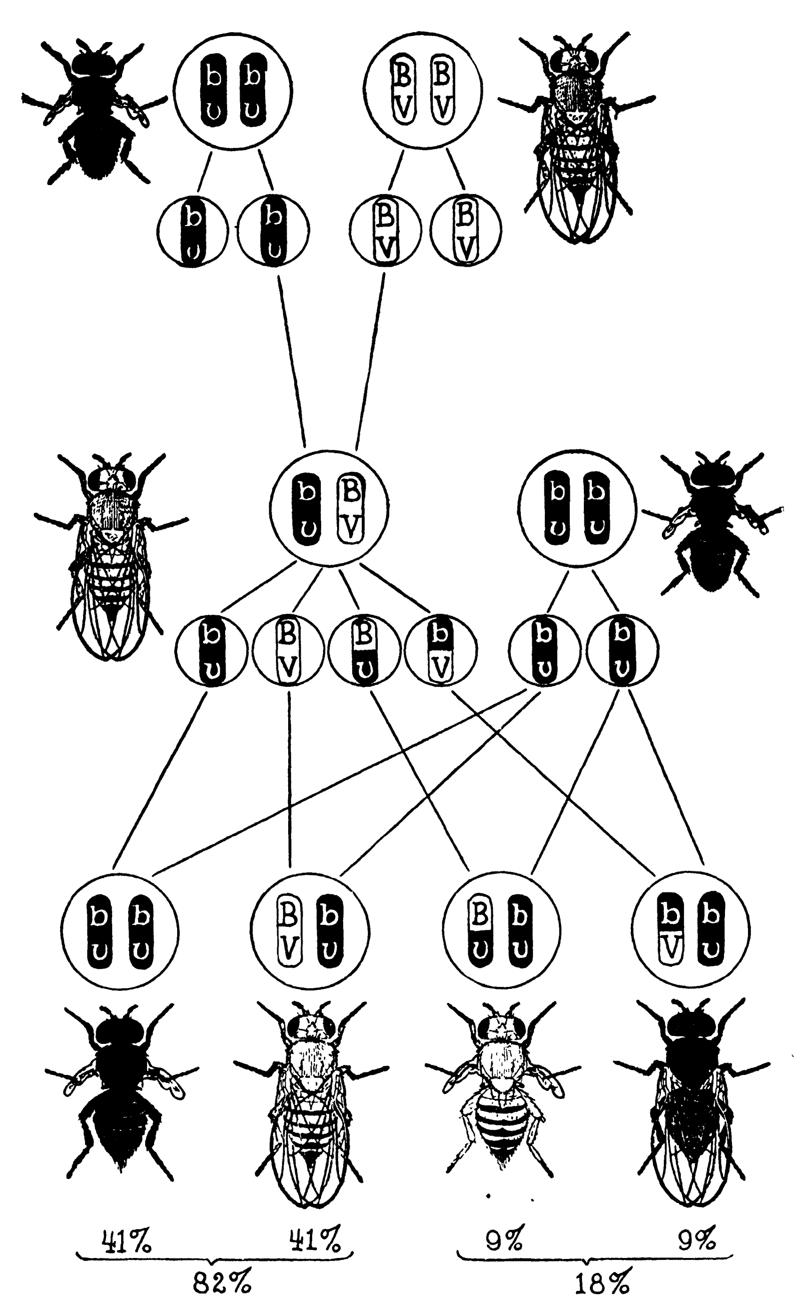


FIG. 312.—Incomplete linkage: F_1 female, from cross of black-vestigial and gray-long, back-crossed to black-vestigial male. (Adapted from Morgan.)

from her homozygous parents and transmitted these chromosomes without change to a large majority of the eggs (Fig. 312). But some of the eggs of the hybrid fly, due to a shift in the gene loci, received $\Big|\begin{smallmatrix} b \\ V \end{smallmatrix}$ and $\Big|\begin{smallmatrix} B \\ v \end{smallmatrix}$ chromosomes, and these eggs gave rise to the minority classes.

An equal exchange of genes between the chromosomes of a homologous pair is called *crossing over;* and crossing over has important genetic consequences. In fact a careful study of the cross-over phenomenon has yielded a determination of the exact sequence of location of virtually all known genes in the different chromosomes of Drosophila.

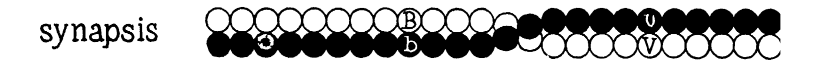
Crossing over takes place during *synapsis* (p. 621) while the homologous chromosomes are entwined about each other so intimately that in many cases they appear to fuse completely. After synapsis it is not possible to *see* that crossing over has occurred, because the members of each synapsing pair are identical in their appearance. But the genetic evidence is altogether convincing. It is known from the law of segregation that the individual genes do not fuse, and that each gene retains its identity without contamination by other genes. But equal blocks of genes may be exchanged between the synapsing mates, as is indicated in Fig. 313. The two chromosomes break at corresponding points, and an exchange of connections occurs at the ruptured points. If the break takes place *between* any two genes, the linkage between these genes is changed. In the present case, for example, this change in the linkage relations is from $\Big|\begin{smallmatrix} B \\ V \end{smallmatrix}\Big|\begin{smallmatrix} b \\ v \end{smallmatrix}$ to $\Big|\begin{smallmatrix} B \\ v \end{smallmatrix}\Big|\begin{smallmatrix} b \\ V \end{smallmatrix}$, in a certain percentage of the gametes.

Localization of the Genes in the Chromosomes. The *frequency of crossing over*—which technically is called the *cross-over value*—provides a valuable index as to the relative distance between any two pairs of genes having loci on the same pair of chromosomes. Cross-over breaks can occur more or less easily throughout the synapsing chromosomes. Consequently, the farther apart are the loci of any two genes, the greater is the likelihood that a cross-over will occur between

them; and conversely, the nearer together are the loci, the less is the chance of a cross-over. Moreover, the cross-over values, expressed on a percentage basis, are *additive* when one studies a given series of genes; and this proves that the loci are arranged in a specific linear order in each chromosome. These important facts are shown, for example, by the cross-over values between

pre-synaptic chromosomes

synapsis



post-synaptic chromosomes

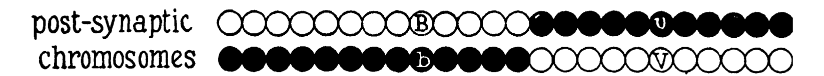


FIG. 313.—Crossing-over. If a cross-over occurs at a point which lies between the location of the genes B and b and that of the genes V and v, these genes, as the diagram shows, will occur in new combinations in the post-synaptic chromosomes.

the genes in chromosome I of Drosophila, which may be summarized as follows:

yellow					
	1.0				
prune		1.5			
	0.5		3.0		
white				5.5	
	1.5				7.5
facet		4.0			
	2.5				
echinus			4.5		
	2.0				
ruby					

Crossing over between two consecutive gene pairs is relatively rare, so that linkage between such genes is almost complete.

But between more distantly localized gene pairs cross-overs are frequent, although, if the distance is too great, the cross-over values are difficult to analyze—because double (Fig. 314), or even triple cross-overs may occur.

The mathematical relation displayed by the cross-over values of the yellow to ruby gene series likewise holds true for *all* genes in each of the other three pairs of chromosomes in Dro-

pre-synaptic chromosomes A F L a f l



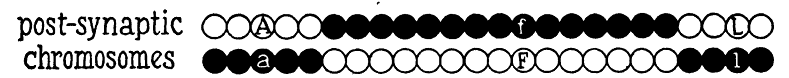


FIG. 314.—Double crossing-over. If cross-over occurs at the points shown in the diagram, the genes A and L, and also a and l, will occur in their original combinations in the post-synaptic chromosomes; but the cross-over will be evidenced by the interchange of the genes F and f at an intermediate locus.

sophila. In fact there is *one, and only one, linear order* which shows this relation. Accordingly, the only possible interpretation of these facts is that the genes are arranged in the chromosomes in a precisely determined linear order, like the beads of a rosary.

As a result of such experiments, accurate *chromosome maps* (Fig. 315) have been prepared for Drosophila and, to a lesser extent, for a number of other organisms. Although Drosophila has been studied much more intensively than other organisms, not all the genes of Drosophila are known. In Drosophila there are probably about three thousand genes, of which about half of those known are shown on the maps. Map I is for the long straight pair of the fruit-fly's chromosomes; II and III are for the smaller and larger of the *V*-chromosomes, respectively; while IV is for the very small pair (Fig. 310). All the genes in each pair of chromosomes assort independently of genes in the

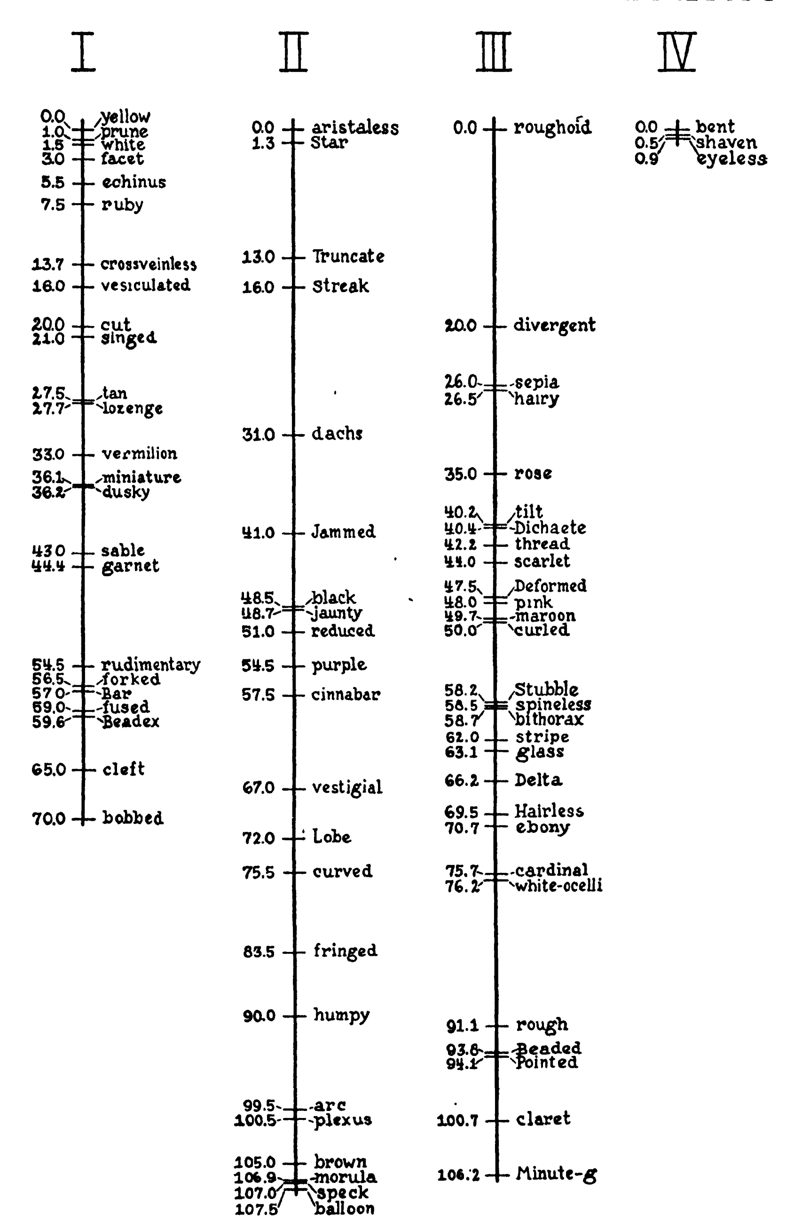


FIG. 315.—Chromosome maps of Drosophila melanogaster, showing the loci of some of the genes which have been most accurately located. (Adapted from Morgan, Bridges, and Sturtevant.)

other three pairs; and the genes localized in each pair of chromosomes display a linked inheritance—which is complete in male animals and incomplete in females. A cytological study of the germ cells during the prophase of the first meiotic division indicates that synapsis, *as it occurs in the male Drosophila,* is more transient and less intimate than is the general rule. But precisely why crossing over is entirely aborted in the male fruit-fly, whereas it occurs successfully in both sexes of almost every other species of animal, cannot be said with certainty.

Morgan's Laws. The phenomena of linkage apply to virtually all organisms, although they were worked out by Morgan and his students mainly in Drosophila. Thus it is customary to designate the last four of the six well-recognized laws of inheritance as *Morgan's laws:*

1. *All the genes of a species can be arranged into linkage groups which correspond exactly to the chromosomes of the species; and the genes in any one pair of chromosomes are assorted during hereditary transmission independently of the genes in the other pairs.*
2. *All genes in the same chromosome are linked in heredity, maintaining their original combinations throughout successive generations, either always (complete linkage), or more often than not (incomplete linkage).*
3. *All the genes in each chromosome can be arranged in just one linear order such that the cross-over frequencies between them have the same mathematical relations as distances between points in a straight line.*
4. *Crossing over at any one point interferes with cross-overs at neighboring points; for short intervals this interference is complete, so that for genes relatively close together in a series, the observed percentage of re-combinations is an accurate measure of the cross-over frequency.*

Inheritance of Sex. As a general rule among sexual organisms, males and females are produced in equal, or almost equal, numbers in every generation; and each of the sexes can mate successfully only with the other.

The inheritance of sex in a majority of organisms shows that a single pair of chromosomes is the differential which determines whether an individual is to be male or female. Actually the situation is somewhat more complex than this, as will become apparent presently. Nevertheless it is certain that the sex differences between individuals of the same species are almost always transmitted via genes, although in the case of some animals, the developmental effects of the "sex genes" are mediated largely through the endocrine glands.

In many species the chromosomes of the female are visibly dissimilar from those of the male. In the *female* Drosophila, for example, chromosome pair number I consists of two straight rods, each the apparent duplicate of the other; but in the *male* Drosophila, one member of pair I is bent, and is plainly longer than the other (Fig. 316). In Drosophila the *sex-differentiating* genes are carried in the chromosomes of pair I. Accordingly these chromosomes are called the *sex-chromosomes,* in contrast to the other *autosomes,* which ordinarily are neutral in their effect upon sexual development. Moreover, the sex-chromosomes of Drosophila are two types; the straight type being called the *X-chromosome,* and the bent type, the *Y-chromosome.*

The sex-chromosomes, like the autosomes, are transmitted to the offspring in the usual fashion, as may be seen in Fig. 316. But due to the dissimilarity between the *X* and the *Y*, equal numbers of males and females are conceived in each new generation of the species. As to their bearing on the sex of the offspring, all the eggs of a female are of one kind, in that all carry an *X*-chromosome. But a male produces *two* kinds of sperm—half *X*-bearing and half *Y*-bearing. When one of the *X*-bearing sperm succeeds in fertilizing an egg, the offspring will be female; but the *Y*-bearing sperm can only give rise to male progeny.

These microscopically visible facts suggest that each *X*-chromosome carries a recessive gene for femaleness, and that each *Y*-chromosome carries a dominant gene for maleness; but this is not true. Actually the *Y*-chromosome has no direct effect in

determining sex. By certain rare abnormalities in the maturation divisions, individuals of Drosophila are produced which have one *X*- and no *Y*-chromosome; and these individuals are always

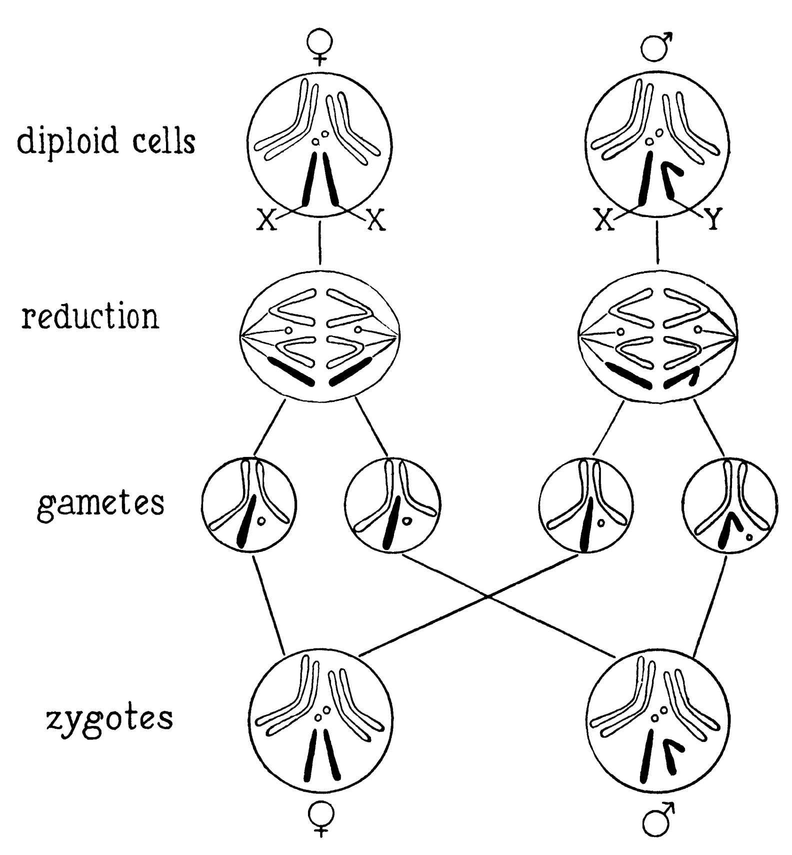


FIG. 316.—Diagram showing the distribution of the sex-chromosomes of Drosophila melanogaster. Sex-chromosomes black, autosomes white.

males. In fact some animals transmit the sex differences in just this fashion; i.e., in males, the *X*-chromosome has no homologous mate. In such cases half of the sperm cells contain an *X*-chromosome, but the other half contain no sex-chromosome (Fig. 317). Occasional individuals of Drosophila (resulting from abnormal maturation divisions) contain two *X*s and a *Y*, or even two *X*s and two *Y*s; and such individuals are always females.

Summarizing the evidence, Drosophila possesses a group of genes which determine the female characteristics of the species, and these "female genes" are localized mainly in the *X*-chromo-

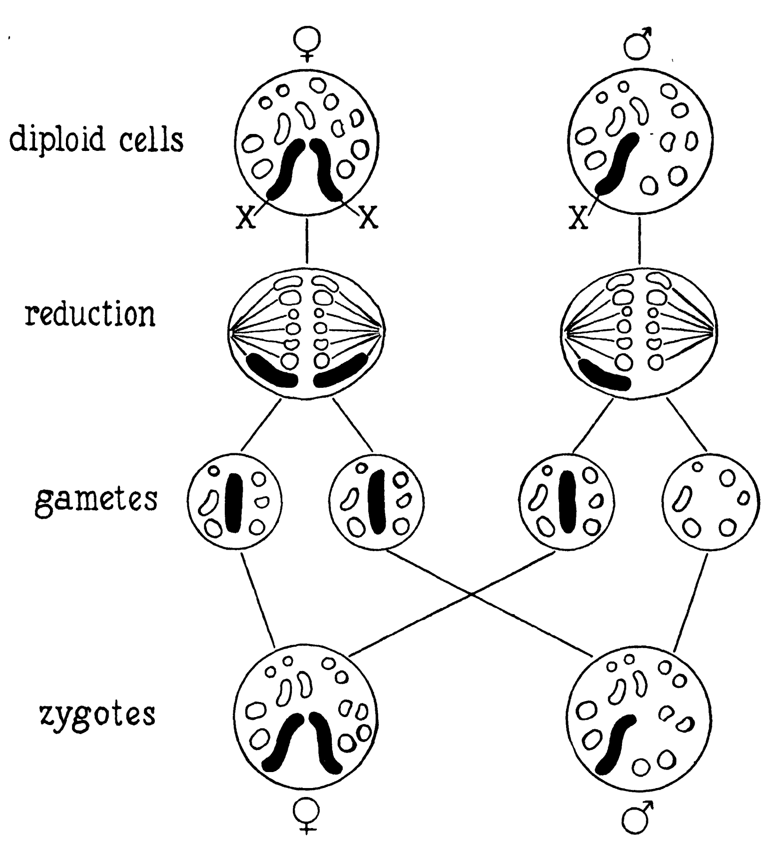


FIG. 317.—Distribution of the sex-chromosomes in Protenor, a bug which has no *Y*-chromosome. Sex-chromosomes black, autosomes white.

somes. The male characteristics, in contrast, are determined by another group of genes, but the "male genes" have their loci mainly *in the autosomes*. All individuals are homozygous for the male sex genes so that no difference is found between males and females with reference to the genes for maleness. Thus the primary sex difference is that females, which receive two *X*-chromosomes, possess a double set of "female genes," and

in such individuals the female characteristics dominate over the male. But male individuals receive only a single set of female determinants, and in these individuals the male characteristics dominate over the female.

In man (Fig. 318) and a majority of other organisms, the sex-determining mechanism resembles that of Drosophila. But in some species the female rather than the male displays a dis-

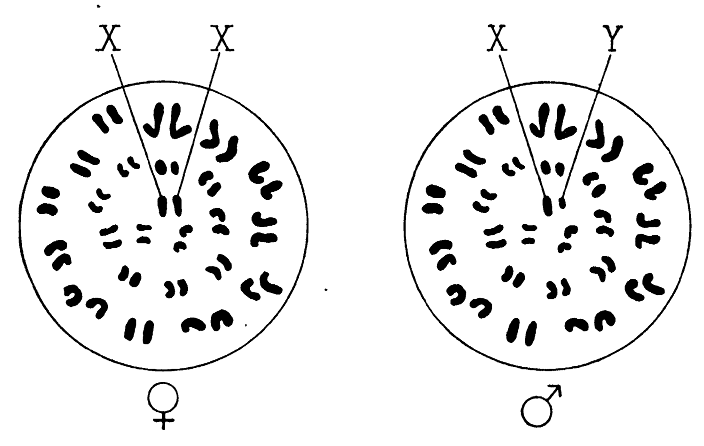


FIG. 318.—Diploid chromosome groups of man. The arrangement of the chromosomes in these figures is diagrammatic. (Adapted from Painter.)

similarity of the sex-chromosomes; although otherwise the mechanism of sex inheritance is similar to that of Drosophila.

Sex-linked Genes and Characters. The *Y*-chromosome of Drosophila, man and many other species, is most unusual. The *Y*-chromosome is not only devoid of sex genes, but also it carries scarcely any other genes. In fact the *Y*-chromosome can almost be considered as a "dummy" chromosome. The *Y*-chromosome has very little influence upon the characteristics of the organism, except that, by replacing one of the *X*-chromosomes, it plays a deciding role in the determination of sex.

The *X*-chromosome, in contrast, carries many genes (Fig. 315). These genes are transmitted along with the sex-determining genes, and consequently a number of hereditary traits tend to be associated with the sex of the individual. Characteristics for which the genes have loci in the *X*-chromosomes are

said to be *sex-linked;* and sex-linkage influences the inheritance of many characteristics—as shown in the following experiments.

In Drosophila, white (*w*) eye color is a sex-linked recessive character, and the allelic gene for red (*W*) eye is dominant. Thus if a white-eyed female (Fig. 319) is crossed with a red-eyed male, all the F_1 daughters are found to have red eyes, but all the sons have white eyes. Moreover, if these F_1 individuals are *inbred,* the F_2 generation gives 25 per cent white-eyed daughters, 25 per cent red-eyed daughters, 25 per cent white-eyed sons and 25 per cent red-eyed sons (Fig. 319). Or if the experiment is started oppositely (Fig. 320)—by crossing a homozygous red-eyed female with a white-eyed male—all the F_1 offspring have red eyes; and in the F_2 generation, all the daughters have red eyes, but the sons show an equal distribution of the red and white eye-color (Fig. 320).

The foregoing experiments show that the inheritance of the eye-color of Drosophila is linked with the inheritance of sex. It is plain also that the *Y*-chromosome, other than displacing the *X*-chromosome, plays no essential role in the determination of the characteristics of the individual.

In man, several types of abnormality, such as *red-green color-blindness* and *hemophilia* (p. 402), are sex-linked recessive characteristics, which are inherited exactly like white eye-color in Drosophila. As to color-blindness, for example, all the sons of a color-blind mother by a normal father will show the defect; although all the daughters will have normal vision. These daughters can transmit color-blindness, however, since none are homozygous for the normal gene. Thus if we designate the recessive color-blind gene as (*b*), and the dominant allelic normal gene as (*B*)—the mother would be (X_bX_b), the father (X_BY), the sons (X_bY), and the daughters (X_BX_b), as to their respective genotypes. In other words, the inheritance of this type of color-blindness follows the same pattern as the inheritance of white eye-color in Drosophila (Figs. 319 and 320).

Non-genetic Sexual Differentiation. A few species display no *genetic* difference between the sexes; and in such cases a zygote can give rise to either a male or a female, depending on

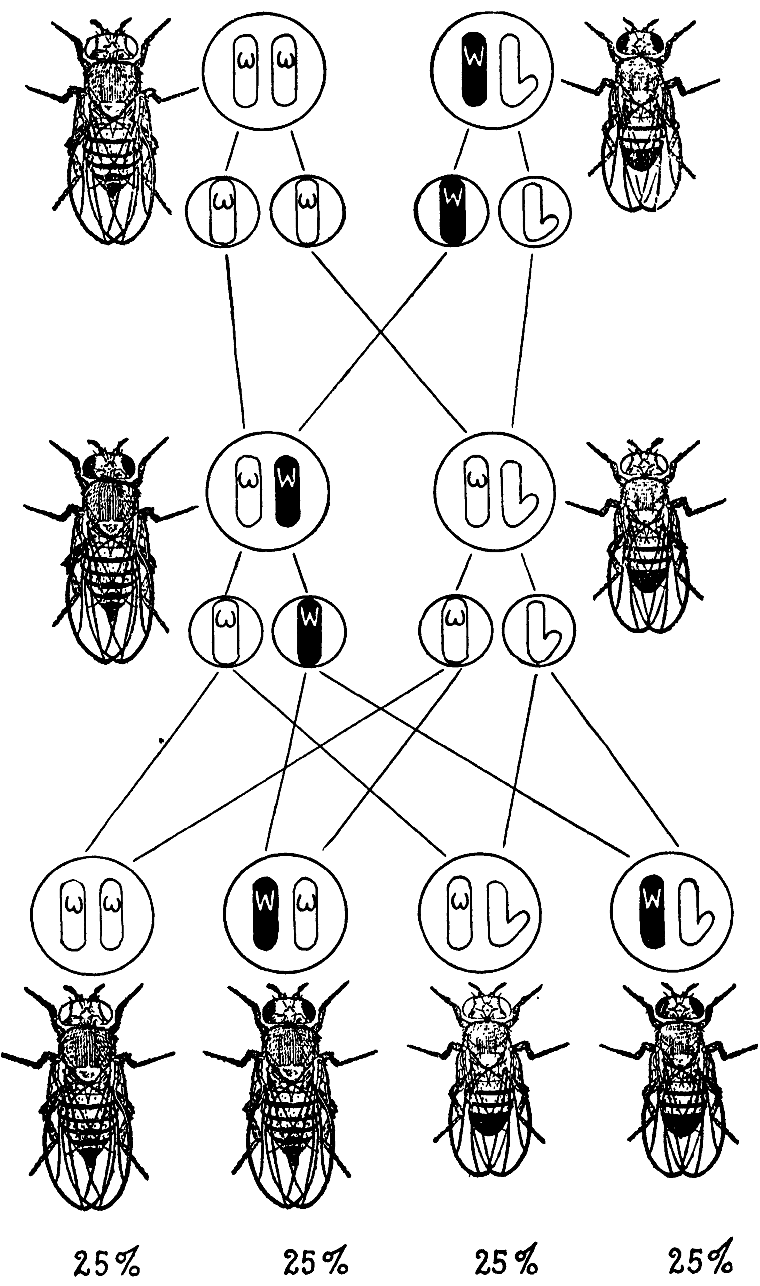
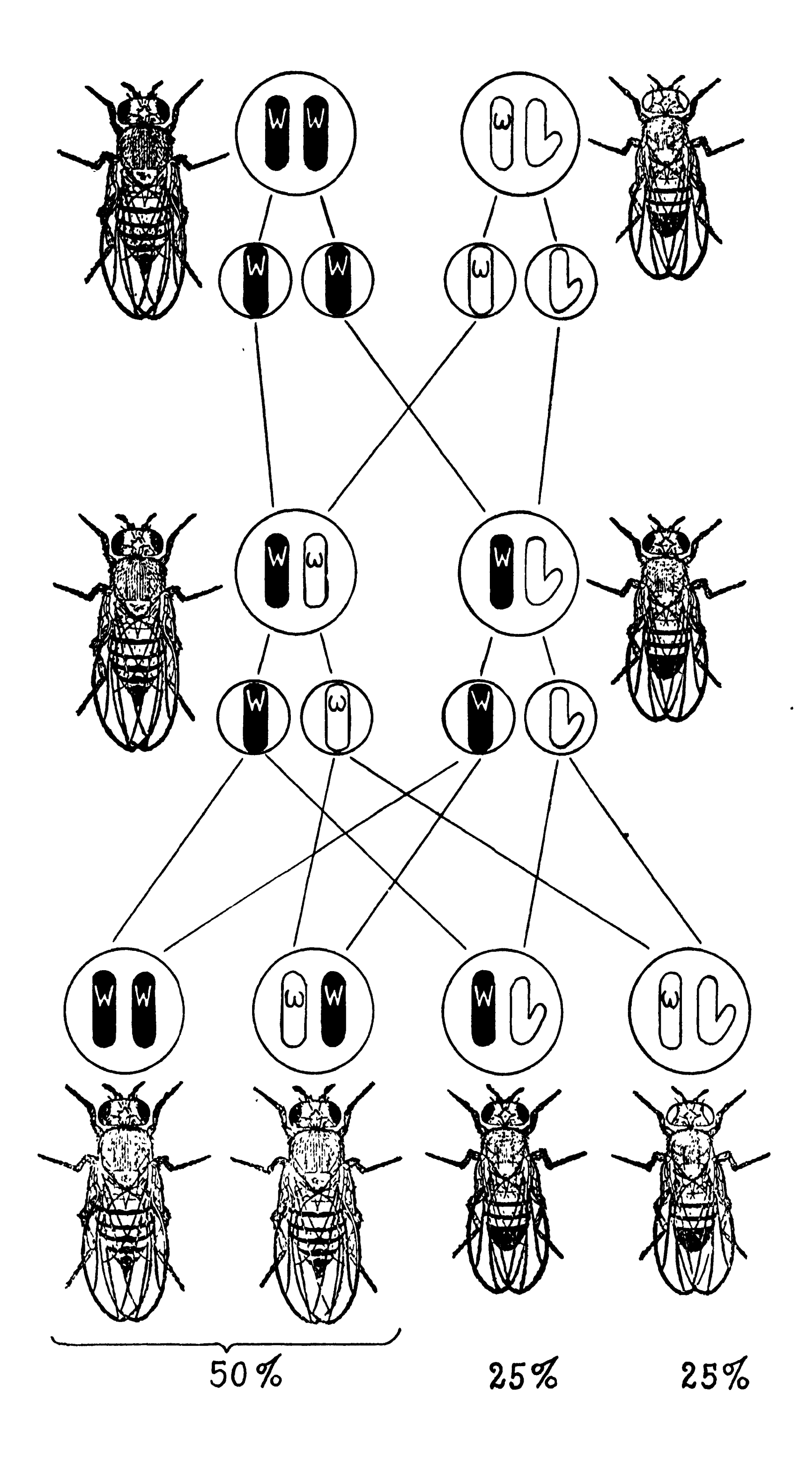


FIG. 319.—Cross of white-eyed female and red-eyed male; F_1 inbred. (Adapted from Morgan.)



W W
ω
W W
ω
W ω
W
W
ω
W
W W
ω W
W
ω
50%
25%
25%

environmental factors such as food. This type of sex determination is quite rare, however, being encountered in only a few worms and other relatively simple invertebrate animals.

Asexual Reproduction in Relation to Heredity. Asexual processes of reproduction—excluding meiotic sporulation and parthenogenesis—tend to produce offspring which are genetically identical. All the cells of the offspring are derived entirely by *mitosis* from the cells of the parents; and the mitotic type of cell division operates to perpetuate the existing combination of genes, affording no opportunity for any recombination of genetic traits.

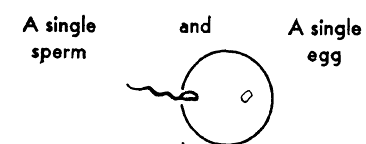
This stability of asexual inheritance is of great advantage in the propagation of commercially valuable plants—such as fruit trees, potatoes, etc. Any cutting or grafting derived from a valuable stock can be relied upon to perpetuate its favorable combination of qualities. Opportunity is not afforded for the loss of advantageous genes, or the gain of disadvantageous ones, because recombination and random assortment can only occur when meiosis is permitted to intravene between the generations. Propagation by seed, even when artificial self-pollination is practiced, usually gives rise to considerable variability among the offspring, because most stocks, unless inbred for many generations, are heterozygous for many genes.

Identical vs. Fraternal Twinning. In a majority of organisms only one individual arises from each fertilized egg; but in a few species (e.g., the nine-banded Armadillo), the embryo regularly divides at an early stage of development, producing two or more genetically identical individuals from the same zygote. This phenomenon of *polyembryony* is not common among higher animals. However, polyembryony sometimes occurs in man and other Mammals, resulting in the production of *identical twins and triplets* (Figs. 321 and 322). Identical twins, in contrast to *fraternal* twins, are always of the same sex. Moreover, identical twins bear a remarkable resemblance to each other, not only as to visible appearance, but also as to characteristics of mind and personality (p. 662).

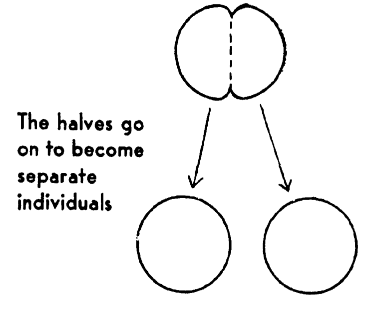
HOW TWINS ARE PRODUCED

IDENTICAL TWINS

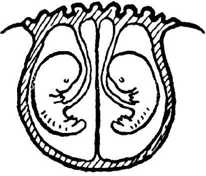
Are products of



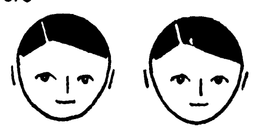
In an early stage the embryo divides



Usually — but not always — identical twins share the same placenta and fetal sac



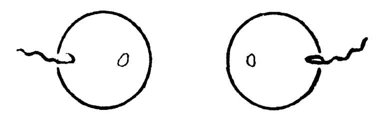
But regardless of how they develop, they carry the same genes and are therefore



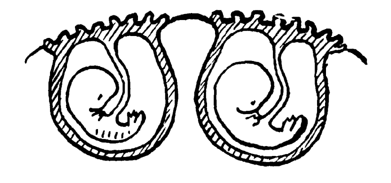
Always of the same sex — two boys or two girls

FRATERNAL TWINS

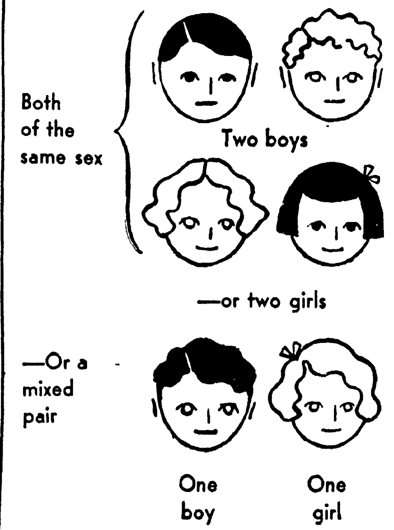
Are products of TWO different eggs fertilized by TWO different sperms



They have different genes and may develop in different ways, usually—but not always — having separate placentas and separate fetal sacs



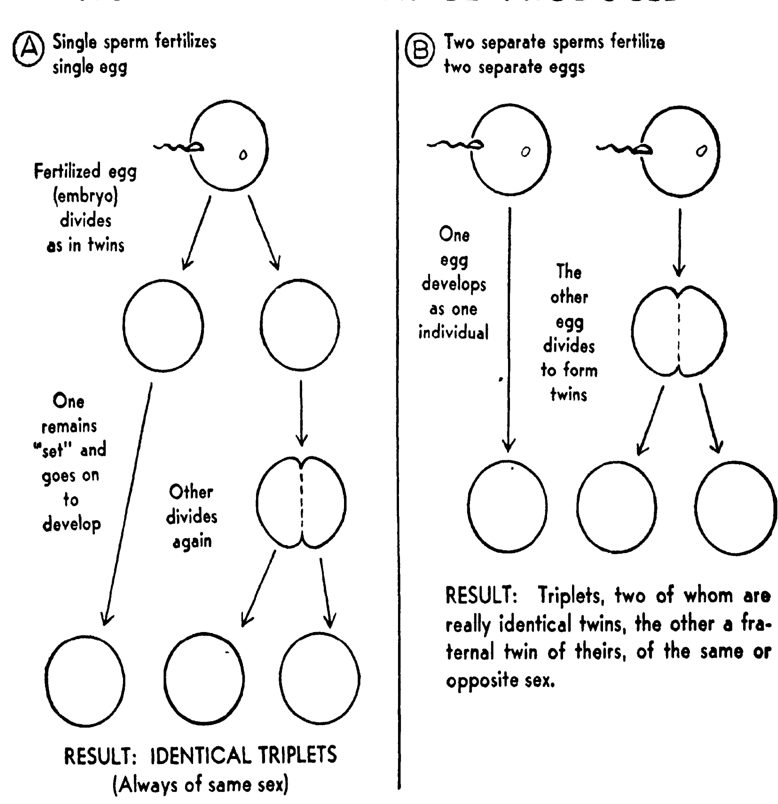
Also, as they are totally different individuals, they may be



From Amram Scheinfeld, *You and Heredity,* by permission of J. B. Lippincott Co.

FIG. 321.

Multiplicity of Genic Effects. Each part and characteristic of an organism is *usually* affected not by a single pair of genes,



From Amram Scheinfeld, *You and Heredity,* by permission of J. B. Lippincott Co.

FIG. 322.

but by several or many pairs. There are, for example, at least fifty different genes which are known to have an influence upon the eye-color of Drosophila; and under natural breeding conditions, all these different genes cooperate in determining the eye-color of the individual offspring.

A cross between red-eyed and white-eyed flies can be called a "one-factor cross" only when the original P_1 stocks are *homozygous* and *similar* as to all other gene-pairs having any influence on the eye color. Deliberately, the stocks selected for most genetics experiments differ from each other by only one hereditary factor; and a long preliminary process of inbreeding is necessary to secure such stocks. In a sense, therefore, the breeding experiments of the laboratory geneticist, which yield such simple ratios among the offspring, are somewhat artificial and arbitrary. Wild flies, obtained directly from their natural habitat, tend to be heterozygous for many eye-color genes, as well as a wide variety of other genes. Consequently many different eye-colors, representing the many possible re-combinations, appear among the offspring. Under these conditions, it is not possible to predict the results of a given mating, as to eye-color, or as to any other selected characteristic. Without the inbreeding technique, therefore, geneticists would not have been able to ascertain the mechanism of heredity, except among a minority of plants, which practice inbreeding (self-pollination) on a natural basis.

It is also important to realize that every gene affects several or many characteristics in the organism. The white-eye gene (*w*), which was used to exemplify sex-linkage, received its name because its eye-color effect is more dramatic and easier to follow than its other effects. Careful study, however, reveals that the white (*w*) gene has many other effects. Flies which are homozygous for this gene lack pigment in many of the internal organs; they develop more slowly and display less vigor than red-eyed flies; and homozygous white-eyed flies produce fewer offspring than their wild type relatives. And what is true of this gene is probably true of all the genes in every organism: each gene has various effects upon many different parts and functions. Thus, to speak of the "gene for white eyes," or the "gene for vestigial wing," is merely to identify a certain gene by its most conspicuous and obvious effect.

Heredity in Man. Great difficulties have beset the scientific study of human inheritance. The impossibility of controlled ex-

perimental breeding, particularly as to the technique of inbreeding; the long period between generations; the relatively small number of offspring; and finally the large number of man's chromosomes—all have combined to hamper the progress of a detailed analysis of human heredity. In fact human geneticists have had to depend largely upon family pedigrees; and frequently such data is biased and otherwise unreliable.

Despite these difficulties, enough has been learned about human heredity to know that the laws and mechanisms are essentially the same as in other organisms. Other Mammals—especially mice, rats, guinea pigs and rabbits—are much more favorable than man for genetic studies; and a vast amount of data proves conclusively that mammalian heredity proceeds along the same lines as were first mapped out in Drosophila.

Most *normal* differences among human individuals—such as size, weight, color of skin, hair, eyes, etc.—are, as in other animals, influenced by many genes; and there are no very closely inbred stocks in man. All human individuals are heterozygous for many genes and consequently it is difficult to forecast the precise distribution of most characteristics among human offspring. Also many characteristics—such as height and weight—are very susceptible to nutritional influences and this makes the genetic analysis more difficult.

In the case of eye-color, which is relatively insensitive to environmental influence, the analysis has been quite successful. *Pure blue* eyes are inherited as a simple recessive, but the various darker shades of eye-color are determined by several other genes—the darker alleles being usually dominant to the lighter. Hair-color and skin-color are likewise determined by several gene pairs. In the case of skin color, all the F_1 offspring of a *pure* white-black cross display a fairly uniform intermediate (mulatto) shade—which shows that each of the original stocks is homozygous for the several skin-color determinants. But the F_2 children, derived from first generation mulatto parents, are of many shades, ranging from pure black to pure white; and it has not been possible to determine the exact number of gene

pairs which are undergoing re-combination, nor to establish the linkage relations of these genes.

The most dramatic *one-factor* crosses in human inheritance are found in the transmission of a number of abnormalities. Polydactyly (extra fingers and toes), brachydactyly (shortened fingers or toes), albinism (absence of pigment from skin, hair and eyes), certain cases of dwarfism, and a number of other relatively rare and deleterious characters—all are transmitted by single pairs of genes. Moreover, the gene-pairs concerned with the transmission of abnormalities tend to be *recessive* in nature. To "remain in circulation," in fact, such deleterious factors are almost necessarily recessive, because dominant abnormalities tend to be "bred out" of the species by a natural tendency of most individuals to choose a "normal" mate.

The inheritance of mental and other less tangible characteristics in the human species constitutes an even more perplexing problem. In the case of mental qualities, particularly, exact measurements are difficult to make; and it is hard to disentangle genetic factors from the manifold influences of the child's environment. The best evidence regarding the inheritance of mental traits comes from the study of *identical twins*, in whom there is an exact duplication of all genetic factors. Such twins, even if they have grown up in separate and different environments, always show a very high correlation of intelligence, as measured by several of the available kinds of "intelligence tests." These measurements are admittedly arbitrary, but they do provide strong evidence that an individual's capacity to learn is largely determined by genetic factors. Other traits, such as are commonly designated as "personality" and "character" are less highly correlated in given pairs of twins. This may merely mean that the measurements of personality and character are not very reliable; or more probably, it indicates that personality characteristics are very susceptible to the modifying influence of environmental experience.

It has often been noted that "feeble-mindedness" and a few forms of insanity show a marked tendency to "run in families"; and the same is true for supernormal talents of one sort or an-

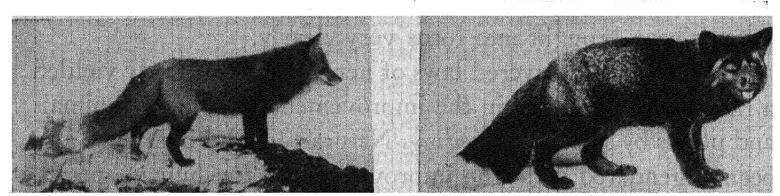
other. But closely related individuals tend to be exposed to the same environment, especially during the formative period of childhood; and the potency of the environment cannot be ruled out under these circumstances. On the basis of our present knowledge, it is possible to say, however, that the mental as well as the physical traits of the individual are determined in highly significant degree by genetic factors; but the details—as to what and how many genes are involved, and as to how the action of these genes may be influenced by disease, malnutrition, education, economic welfare, and other environmental factors—have not yet been brought into focus very clearly.

The recently discovered laws of heredity have already yielded a rich practical harvest in the improvement of domestic animals and plants by *selective breeding*. Naturally high hopes have also been engendered as to the improvement of the human species. But these hopes are hampered by enormous difficulties. Our knowledge of human heredity is still relatively meager as to detail, and also there is no agreement as to what goals should be "bred for" in any large-scale eugenics program. As to an ideal feminine type, for example, college men might insist upon the slim exotic beauty of some current "pin-up" girl; whereas a "Hitler" might want to foster the sturdy and fecund qualities of a peasant mother. Moreover, mankind is adverse to tampering with individual rights and preferences; and it does not seem likely that human matings will ever be governed simply by the dictates of genetic principle. Accordingly, the greatest hope for human advancement, at least in the near future, still lies in the amelioration of the social, educational, and economic conditions of human life.

Mutations. All the facts of heredity emphasize the *stability* of the genes, since the genes of a species are generally transmitted without change through many successive cell divisions, and through many generations of the organism as a whole. All the genes of the zygote multiply successively as the many cells of the developing embryo are formed, so that every cell of the adult receives a duplicate of every gene originally present in the zygote. Moreover, every gene in the diploid germ cells of the

organism has an equal chance of passing on into the next generation by way of the gamete cells of the current generation.

But the stability of genes is by no means *absolute.* On rare occasion a certain gene may change, suddenly and dramatically, into a new and different gene. This important phenomenon is called *mutation.* As a result of mutation, a new hereditary factor will suddenly appear, and this new gene will influence the destiny of the species in a small or large degree, depending on the nature of the change. Quite a number of drastic mutations are



Courtesy of the American Museum of Natural History, New York

A B

FIG. 323.—The silver fox (A), which has a highly valued pelt, arose by mutation from the wild-type red fox (B).

known to have played an important role in animal husbandry. Mutant stocks of domestic animals—such as hornless cattle, short-legged Ancon sheep, and white turkeys—have distinctive new features which are more desirable than those of the original stock (Fig. 323).

A mutation gives rise to a new gene which *usurps the locus of the old.* Consequently the mutant gene becomes allelic to the normal gene from which it has arisen. In diploid cells, only one gene of any allelic pair has been known to mutate at a given time; and the mutant gene may bear either a recessive or a dominant relation to its non-mutated mate. In any event, the mutant gene immediately occupies the old position in a particular chromosome; and thereafter the mutant gene enjoys the same linkage relations as its normal progenitor. In Drosophila many mutations have arisen in pedigreed stocks kept under meticulous observation, so that in each case it is possible to specify which gene is the mutant, and which is the normal allele. For example, the gene (w) which determines white-eye mutated

from (W), the red-eye gene; and the gene (b) for black-body came from (B), the gray-body allele. Nevertheless, little distinction exists between a mutant gene and the normal original, except that the former is known to have arisen from the latter. In wild stocks, wherein no pedigrees are known, it is not possible to tell which member of an allelic series is the "original," and which are the mutant genes. In fact a study of evolution from the viewpoint of heredity leads to the conclusion that *virtually all* genetic differences—between individuals of the same species, and between the different species—have resulted from an age-old series of mutations extending back to the beginnings of life.

The sudden and unexpected appearance of a new heritable characteristic in a known stock does not always indicate a mutation—in the strictest sense. Such changes sometimes result from chromosomal *duplications* or *deficiencies*, such as arise from abnormalities in the divisions of the germ cells; or they may come from the deterioration of one or more genes in the germ cell line. These phenomena are sometimes called "mutations"; but a stricter usage, confining the term mutation to the transformation of one gene into another, will be adhered to in the present account.

Mutations are recognized by their phenotypic effects, but recessive mutants do not produce these effects until the next generation; i.e., until homozygous offspring have been produced. Mutations may also occur in the somatic cells of the organism, but in this case the effects are usually limited to some particular part or parts of the body; and such changes are not perpetuated in subsequent generations. Thus, a somatic mutation usually produces a *mosaic* organism, such as a Drosophila having a red eye on one side and a white eye on the other.

The phenotypic change induced by a mutant gene may be so slight that it can be detected only by extremely careful study; or the change may be drastic enough to kill the organism. On the basis of the degree of phenotypic change (induced by the mutant when it is homozygous), mutations are usually classified as (1) *slight mutations*, which can be recognized only by statis-

tical analysis, and other special methods; (2) *visible mutations*, which can be recognized at a glance; and (3) *lethal mutations*, which are so drastic that the organism dies before reaching sexual maturity.

Mutation Frequencies. Rare though they are, mutations are not so rare as was first supposed, *if all types are considered.* In Drosophila melanogaster, some 500 different *visible* mutations were distinguished in surveys covering 25,000,000 individuals of known genetic stock; i.e., about 1 fly in 50,000 plainly showed a mutant quality. And when special methods were employed for the detection of *lethals,* this type of mutation was found to occur about six times more frequently than the visible mutations. There are no exact methods for estimating the frequency of slight mutations, but many experts believe that slight mutations may take place even more often than either of the other types. Furthermore, there is no evidence to indicate that mutations occur any more frequently in Drosophila than in other organisms generally.

The same gene may mutate successively in several different directions, giving rise to a *series of allelic genes.* In the fruit-fly, for example, the gene *W*, the normal allele of white (*w*) gene, has given rise to 11 mutant alleles, each having a different effect upon eye-color, and upon other phenotypic characteristics. Several of these mutations have been duplicated, in different stocks on different occasions; and in some cases the same mutant has arisen from two different alleles. Thus in the white (*w*) series, the gene w^e (eosin) has arisen not only from *W* (red) but also from *w* (white); and eosin has mutated back to white and also to red.

As a general rule the mutant gene has its chief effects upon the same part or character as the normal counterpart, though the effects may vary widely as to quality and intensity. Except for this fact, however, mutations appear to be quite random in their phenotypic effects; and this is probably why so many mutations are lethal in result. In the delicate balance of developmental and functional processes in a complex organism, any con-

siderable change is more likely to "gum up the machinery" than merely to modify its operational behavior.

Little is known as to the causes of mutation, although the frequency of mutation is known to increase at higher temperatures; and also the mutation rate is much higher when the organism is exposed to short-wave radiations such as X-rays and radium emanations. The heat response, within the range which the organism can tolerate, approximates a threefold increase of the frequency of mutation, for each 10° elevation of the temperature. This high degree of temperature sensitivity is strong evidence that a chemical rather than a purely physical reaction is involved. Moreover, each mutation is in all-or-none change, in which the gene behaves as a single unit. As a whole, therefore, the evidence indicates that the gene is either a single molecule, or a small group of molecules specifically organized as an integral unit.

Genetic Variations. Even among offspring of the same parentage the interplay of genetic and environmental factors results in great variation among organisms—and this accounts for the familiar fact that no two organisms are ever *exactly* identical. But sharp distinction must be made between *environmental variations*, which are not perpetuated by the mechanisms of heredity, and *genetic variations*, which are so perpetuated. Environmental variations are referred to more technically as *modifications;* but the importance of modifications will be discussed later (Chap. 26).

The following classification serves to summarize and systematize the several kinds of *genetic variations* which have been mentioned during the discussion on heredity:

1. *Recombinations.* Differences among offspring due to segregation, independent assortment, crossing over, random fertilization, and other *normal* operations of the chromosomal mechanism.

2. *Aberrations.* Variations due to occasional *irregularities* in the behavior of the chromosomes.

3. *Mutations.* Transformations by which one gene changes into another.

Recombination. The numbers of different phenotypes and genotypes produced in several simple crosses were analyzed previously. These results may be extended and generalized as follows. Assuming the absence of *complete* linkage (and this is generally true), any organism which is heterozygous for n pairs of genes will produce 2^n genetically different kinds of gametes. Or if one parent is heterozygous for m pairs, and the other for n different gene pairs there will be $2^{(m+n)}$ different genotypes among the offspring. Or if both parents are heterozygous for the same n pairs of genes, the number of genotypically different offspring will be 3^n. If dominance is entirely lacking, the numbers of phenotypes and genotypes will be equal; otherwise the number of phenotypes will be less, although the recessive genes will all appear in subsequent generations.

In general, therefore, the number of genetically different offspring increases more and more rapidly as the parents become heterozygous for more and more gene pairs; or in mathematical language, genetic variation increases exponentially with heterozygosity.

Only a small minority of species are self-fertilizing; and a majority of organisms, as a result of random mating, are heterozygous for many genes. Under these conditions, consequently, the production of two genetically identical offspring becomes virtually impossible, except where more than one individual arises from the same zygote (identical twins, triplets, etc.). In man particularly, owing to random mating and the conservative rate of breeding, genetic identity between any two children lies quite beyond the range of practical possibility.

Aberration. The processes of mitosis and meiosis are extremely precise and regular, but now and again a slip-up may occur while the countless cells of the species proceed with their divisions. Sometimes a chromosome, or a whole set of chromosomes, may be gained, lost or misplaced; or just a fragment of a chromosome may experience a similar fate. Moreover, if such an *aberration* occurs in the cells of the germ cell line, a a new and different complex of chromosomes will automatically

be transmitted to the offspring; and the changed genetic constitution of the species will be perpetuated.

The commonest and most important type of aberration involves the gain of one or more *whole sets* of chromosomes. This may result if a nucleus fails to divide after the chromosomes have divided, or if two daughter nuclei fuse before the cell divides. Such an aberration occurring in a germ cell may lead to the production of *diploid* ($2n$) gametes. Such gametes give rise to *triploid* ($3n$) offspring if fertilized by normal (n) gametes; or to *tetraploid* ($4n$) offspring if fertilized by other diploid gametes.

Both triploid and tetraploid individuals have been found in many species (Fig. 324). Tetraploids particularly are apt to be larger than their diploid prototypes; and a number of other phenotypic differences may accompany the aberration.

As to the production of gametes, triploid and tetraploid individuals differ quite markedly. Usually all the gametes of a tetraploid are diploid, and all are capable of taking part in fertilization. But the gametes of a triploid individual vary as to their chromosome count, all the way from n to $2n$, with a *majority* falling in the intermediate range. And since only the n and $2n$ gametes can participate successfully in fertilization, *triploid individuals are highly sterile.*

In nature many tetraploid stocks are found among plants, but very few animal tetraploids occur. Among cross-fertilizing species there is little chance that both parents should simultaneously produce aberrational ($2n$) gametes; and unless this occurs the aberration is almost certain to be eliminated in the next generation, due to the sterility of the triploid offspring. But among self-pollinating plants, a single aberration may reach both the male and female gametes, and thus tetraploidy has a fair chance of becoming established in such species. In fact quite a number of species in closely related plant groups have chromosome numbers which are multiples of a common factor (Fig. 325). In any tetraploid stock, subsequent aberrations occurring over a period of many years may result in the production of

other stocks which are hexaploid ($6n$), octaploid ($8n$) and so forth.

Other types of aberration, which also can be important in the origin of species, display quite a variety of forms (Fig. 326).

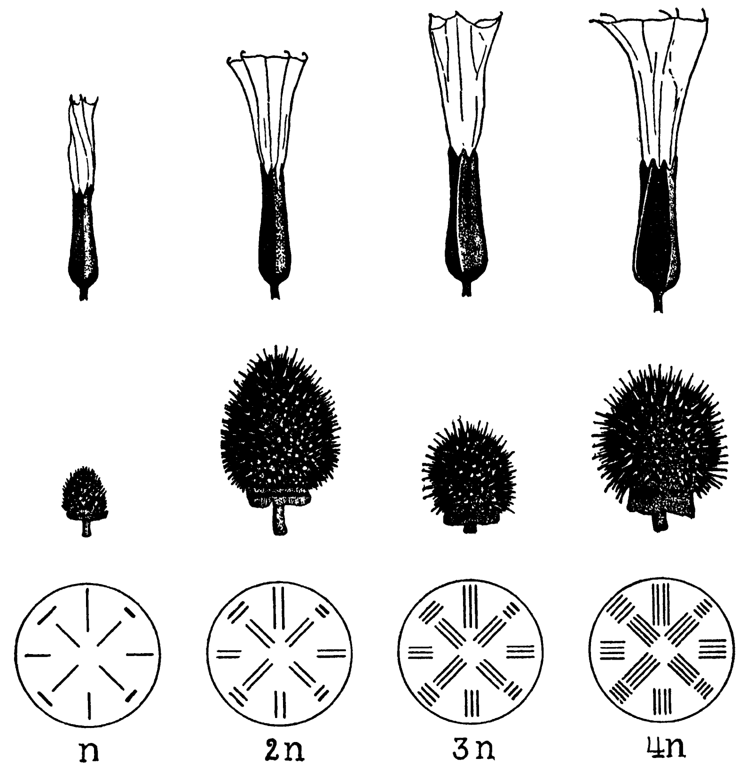


FIG. 324.—Flowers, seed capsules, and chromosome groups of haploid, diploid, triploid, and tetroploid Jimson weeds (Datura stramonium). The small size of the seed capsules of the haploid and triploid plants is due to the low fertility of these forms, producing relatively few seeds. (Adapted from Blakeslee)

Deficiencies, due to the loss of one chromosome, or any fragment of a chromosome; *duplications,* due to the presence of an *extra* chromosome or any of its pieces; *translocations,* due to the attachment of a piece to some other chromosome; and *inversions,* due to the re-joining, by the wrong ends, of two pieces of

a single chromosome—all have important genetic consequences which have been studied very intensively in Drosophila. Irradiation of animals and plants with X-rays greatly increases the occurrence of such aberrations, since the X-ray treatment tends to produce a fragmentation of the chromosomes. Careful stud-

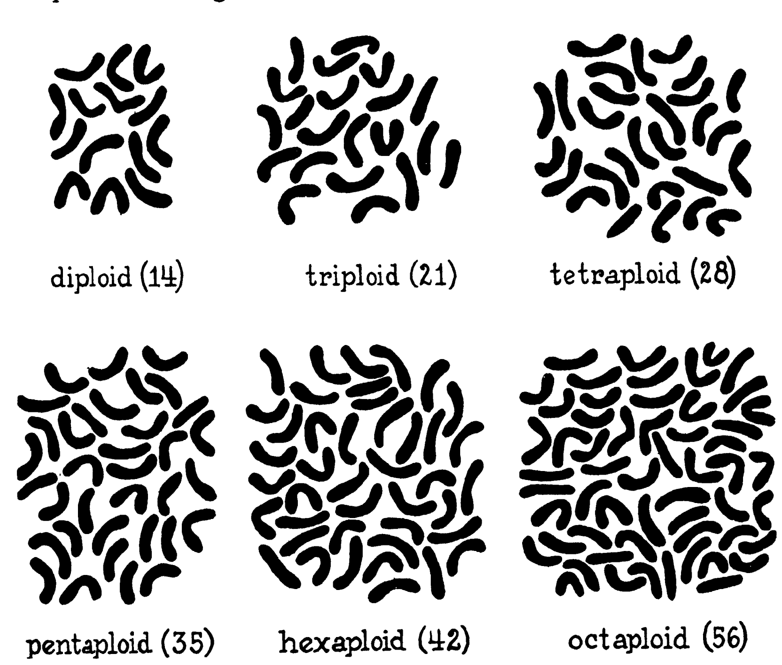


FIG. 325.—Chromosome groups of different species of roses. Some of these forms (those with odd chromosome numbers, at least) are probably hybrids. (After Tackholm.)

ies of the chromosomes of several closely related species have shown that the difference between two *species* may, in some cases, arise suddenly by chromosomal aberration. In one case, for example, a single inversion occurring in just one chromosome produced a new stock which was sufficiently different from the old to be considered as a separate species.

Selective Breeding: Artificial Selection. Except for species with a long history of self-fertilization, animal and plant populations tend to be extremely mixed; i.e., composed of individuals which are heterozygous for many different pairs of

genes. In consequence of this heterozygosity, most species display a high degree of genetic variability; and such species are very plastic from the viewpoint of experimental breeding.

Artificial selection has produced many "breeds" of animals and plants, according to man's need or fancy. Attempts to improve the quality of domesticated animals and plants were started long before the laws of heredity were understood, and many valuable breeds were created by hit and miss methods.

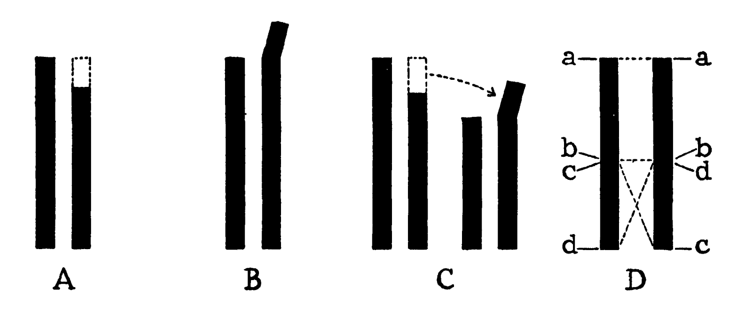


FIG. 326.—Types of aberrations. In each case the normal chromosome is shown on the left, the abnormal one on the right. A, deficiency; B, duplication; C, translocation; D, inversion.

However, modern genetics has greatly accelerated the processes of selective breeding, because modern breeders select their crosses logically and efficiently, according to the laws of segregation, assortment, linkage, etc. Accordingly, it is now possible to "pick apart" the hereditary qualities of a given species and to assemble its desirable qualities into a new stock which can be depended upon to breed true in subsequent generations.

Animal breeding is difficult because none of man's domestic animals can be self-fertilized. However, pure lines of true breeding animal stocks can eventually be obtained by persistent and continued *inbreeding*. Strictly speaking, inbreeding involves brother-sister matings in every generation; but in practice first cousin crosses are more frequently employed. The final goal of the inbreeder is to establish complete homozygosity with reference to all gene pairs which have any effect upon the qualities of the organism which are being "bred for." In the case of self-fertilizing species this goal may be reached in six generations

of inbreeding; but brother-sister inbreeding requires about three times as many generations; and cousin crosses even more.

To take a crude example, suppose that the problem is beef production; and the cattleman owns a large herd with a long history of *random* mating. In this case, the muscle weight of the herd would show tremendous variation between the heaviest and lightest animals. If the two heaviest specimens of the herd are selected as parents, the offspring will still vary widely as weight, but the average *weight* of the selected group will be greater than that of the herd as a whole. Similarly if the two champions of the selected group are crossed, the average weight of the F_2 selectees will be still greater. Finally, however, after about twenty generations of such selective inbreeding, a maximum weight will be reached. Continued inbreeding will maintain the heavily meated stock, but further improvement will not occur. The stock has become homozygous for all genes concerned with muscle weight and, therefore, no further improvement can be expected, except on the rare chance of a favorable mutation, or aberration. The breeder must now resort to *outcrossing* with the champion of some other famous pedigreed herd, in hopes that a still more favorable combination of "meat genes" may be obtained. If so, the process of selection may proceed again until a peak of homozygosity is gained in the new and better stock.

In practice, the problem is not so simple as is indicated by the foregoing description. The breeder must simultaneously select for other qualities in addition to "meat weight." Of what avail is a meat champion, if the new stock is susceptible to disease, cold, or other unfavorable environmental factors; or if the stock displays a reduced capacity to multiply? In fact the very process of inbreeding may lead to a decrease in the general vigor of the inbred line as compared to the mixed population, unless the breeder pays close attention to the factors of health and resistance in making his parental selections. The tendency of an inbred stock to lose vigor is not due to inbreeding as such, but to an accidental accumulation of deleterious recessive genes as the degree of homozygosity increases. Unfavorable recessives are

apt to be widely spread in any mixed population, since heterozygous individuals, which suffer none of the injurious effects, continue to act as carriers. But inbreeding tends to increase homozygosity and there is always a good chance that unfavorable recessives may become homozygous in the selected stock. On the other hand, it is quite possible, by selecting only the most vigorous and fertile individuals of each generation, to produce a highly inbred line which is superior to the original mixed population as to general health, vigor and fecundity.

The results of artificial selection can be most startling. Among dogs, for example, one can scarcely believe that the "pocket Mexican hairless" belongs to the same species as the gigantic Great Dane. But always a limit is reached as to how far a certain quality may be carried in a given direction; and barring mutations and aberrations, this limit cannot be exceeded by selection. Artificial methods of increasing the frequency of mutations are too recent to have yielded any practical results; but perhaps these methods can eventually be adapted to utilitarian purposes.

The Gene in Relation to Development. To ascertain the *mechanics of development*, and to determine how, when, and where the genes produce their developmental effects, has long been the general aim of *experimental embryology*. No detailed solution of this problem has yet been reached, although some general questions have been answered.

A main question concerns the manner in which the cells and parts of the developing embryo eventually become differentiated into the tissues and organs of the adult organism. All the cells of an embryo receive an identical set of genes; yet sooner or later some cells become nerve tissue, others become muscle, others epithelium, etc.—and the destiny of each tissue differs in each different region of the embryo.

In general, the genes received by a certain cell determine the *potentiality* of its development, but the environment of the cell determines the *actuality* of its destiny. Sooner or later the genes in the different cells of the young embryo are subjected to many small differentials in the local environments, depending upon

the position of the particular cells in the embryo; and these factors play a crucial role in the processes of differentiation.

The cytoplasm represents a part of the environment of any set of genes; and a given set of genes may produce totally different effects on account of small differences in the composition of the surrounding cytoplasm. Even at the time of fertilization there are always significant differences in cytoplasmic composition at the poles of the zygote. Moreover, the cytoplasm of the animal pole goes mainly to an upper group of cells , during normal cleavage (Fig. 156); and the cytoplasm of the vegetal pole goes to the lower cells. Inevitably, therefore, differences occur between the cells at a very early stage of development. And as development continues, many other differentials develop in the genic environments of the various regions of the embryo. The chemical environment is not uniform, since some cells come to lie in a more advantageous position with reference to the supply of oxygen and other nutrients; and some cells have an easier problem in disposing of their metabolic wastes. Also, the distribution of physical factors, such as pressure (from other cells), light, heat, electric fields, etc., do not impinge uniformly upon the different cells. All these chemical and physical forces appear to cooperate in determining the differential action of the genes in the different cells of the embryo. One main problem in experimental embryology is, therefore, to determine which of these environmental factors play crucial roles in the differentiation of particular structures; and when this control is exerted in the case of each different kind of cell.

Pressure from neighboring parts of the embryo may greatly influence developmental processes, as is demonstrated by a classic experiment on the frog's egg. If the two blastomeres are separated in the two-cell stage of development, both of the separated cells develop into small but perfectly *whole* embryos. But if one of the two cells is merely killed and left in contact with its companion, the remaining cell develops into only *half* an embryo. This shows that pressure, or at least some other factor emanating from the contiguous cell, dead though it be,

has had a very profound influence upon the developmental destiny of all the other cells of the embryo.

Determination. Sooner or later, each cell in the embryo finally "takes its destiny into its own hands" and becomes *determined* as to its eventual differentiation. But the time at which *determination* occurs differs widely in different embryos, and in the different cells of the same embryo. In a few embryos, the cells are determined very early, even at the two-cell stage—in which case each of the separated blastomeres can give rise to only half an embryo. But in most cases a determination of the cells comes much later in the embryonic period.

In the frog embryo *during gastrulation* (p. 326), small groups of cells may be *transplanted* from almost any part of the embryo and induced to grow in various new positions in the same embryo. Such transplanted cells always change their destiny and develop into structures which are normal for the region *to* which they have been moved. But if similar transplantations are made at a later stage, the results are altogether different. Now the transplanted cells give rise to structures characteristic of the region *from* which they have been moved. The cells of a *limb* bud, for example, moved from the shoulder region to the side of the abdomen, now cling to their original destiny, giving rise to a fore-limb which is quite normal, except for the peculiarity of its position. At some time between gastrulation and the appearance of the limb bud, the cells have lost their *totipotency* and have become *determined* as to their eventual destination.

Embryonic Organizers. One group of cells in the frog embryo becomes determined much earlier than the others. Toward the end of gastrulation the cells constituting the *dorsal lip of the blastopore* (Fig. 327, E), if transplanted to another part of another embryo, go on developing in the same manner as they would have done, had they not been moved. Moreover, the transplanted *dorsal lip* determines not only its own development, it also *organizes* the development of the neighboring cells. Soon an *extra* neural tube begins to form in the host embryo, behind the site of the transplanted dorsal lip (Fig. 328); and a secondary vertebral column, together with associated

structures, is *induced* to form in an entirely foreign region of the embryo. In fact the organizing capacity of the lip region can be traced back before gastrulation. If the corresponding part of a fertilized egg be removed, such an egg never develops into

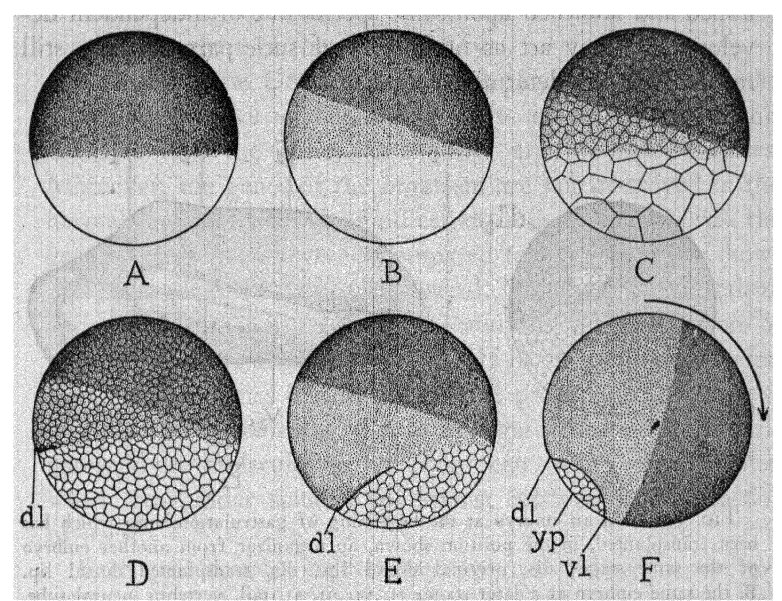


FIG. 327.—Early development of the frog. A, unfertilized egg; primary axis vertical, with animal pole above, and vegetal pole below. B, after fertilization and appearance of the gray crescent; secondary axis horizontal, with gray crescent at the left; median plane in the plane of the page. C, blastula; cells above smaller than those below, those at the left smaller than those at the right. D-F, gastrulation; during gastrulation the whole embryo rotates as indicated by the arrow, so that the primary axis, originally vertical, becomes the longitudinal axis, with the pole at the anterior end, and the secondary axis, originally horizontal, becomes the dorso-ventral axis, with the original gray crescent region on the dorsal side. dl, dorsal lip of the blastopore; vl, ventral lip of the blastopore; yp, yolk plug.

anything but a ball of cells; whereas if other small parts of the egg are taken away, the egg still gives rise to a normal, or approximately normal, embryo.

After gastrulation, other parts of the embryo, especially those lying near the primary organizer, gradually become determined. Soon a bit of ectoderm, transplanted from the dorsal surface quite some distance posterior to the blastopore, will develop into

nerve-cord regardless of its new location. Moreover, this ectoderm acts as a secondary organizer in that it determines not only its own development, but also that of nearby parts. And in like manner, other parts of the embryo, once they have been determined and launched upon some special line of independent development, may act as organizers of such parts as may still remain in a non-determined state.

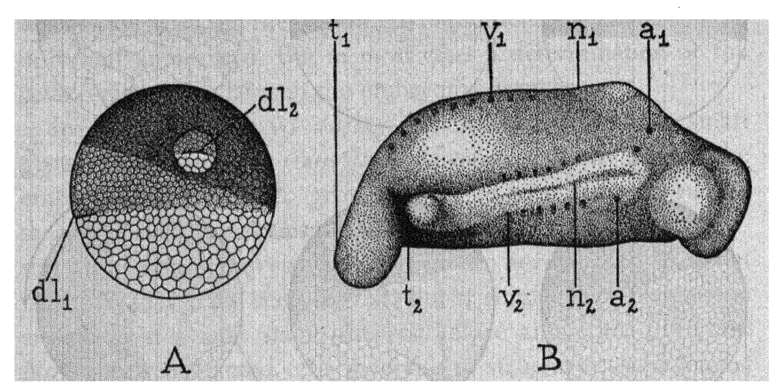


FIG. 328.—A, an embryo at the beginning of gastrulation, into which has been transplanted, in the position shown, an organizer from another embryo of the same stage; dl_1, original dorsal lip; dl_2, transplanted dorsal lip. B, the same embryo at a later stage; t_1, v_1, n_1, a_1, tail, vertebra, neural tube, and auditory vesicle, in their normal positions, developed under the influence of the original organizer (dl_1); t_2, v_2, n_2, a_2, tail, vertebra, neural tube, and auditory vesicle of the secondary embryo, developed under the influence of the transplanted organizer (dl_2). (Adapted from Spemann.)

Precisely how an organizer "organizes" is quite unknown. Recent experiments show that dorsal lip tissue will induce the formation of a neural tube even if the tissue is *killed* before it is introduced into the host embryo. In fact, supernumerary neural tubes have been induced by a variety of chemical and physical agencies, which are quite foreign to the normal embryonic environment. At present, all that can be said is that the organizer introduces some kind of differential into the environment of the genes of neighboring cells, and this differential induces a change in the subsequent behavior of these genes. Certainly the different parts of an embryo have ample opportunity for affecting one another: mechanically, as a result of mutual

pressure; chemically, as a result of differences in the rates and qualities of metabolism; electrically, by way of bio-electric phenomena; and so forth. Moreover, other forces which are still unknown may play upon the genes in the different parts of the embryo, determining the course of their performance within the sphere of their potentiality.

Nature of the Gene. The nucleus plays an important role in the constructive metabolism in every cell (p. 38); and this indicates that the genes, essentially, are *chemical* agencies. Moreover, the genes of the organism are not destroyed in the normal course of their chemical activity; or, in other words, the genes behave like *enzymes*. Compared to other enzymes, however, the genes are somewhat special. Other enzymes catalyze various reactions, but each gene catalyzes the production of itself. All genes have the power of self-increase or—in chemical terminology—genes display the unique property of *autocatalysis*. Each gene, accordingly, is to be regarded as either a single autocatalytic molecule, or a closely knit group of molecules, which can, under suitable conditions, catalyze the production of itself.

Each gene doubles itself between successive divisions in every cell; and on the theory that this doubling is an autocatalytic process, the reaction may be written:

$$G + a + b + c + \cdots \rightarrow 2G + d + e + f + \cdots$$

where G represents a certain gene; a, b and c, etc., are substrates used in the synthesis; and d, e and f, etc., are by-products of the synthesis. Some or all of these substances may be important in the cell, catalytically or otherwise, as participants in the metabolic reactions which result in the appearance of the visible phenotypic effects of the particular gene. But if an allelic gene, G^1, were to be substituted for G, a change would be expected in the substances consumed and produced by the autocatalysis; and this in turn would effect a change in the phenotypic end-results. There are, of course, many other ways in which genes might affect the metabolism of the cell—by catalyzing other reactions independent of their autocatalytic synthesis or by over-

producing themselves and then disintegrating into catalytically active decomposition products, etc. These questions, however, cannot be settled on the basis of our present knowledge.

Every gene is present in every diploid cell of the organism, and therefore every gene inevitably has some effect upon the metabolism of every cell. More or less constantly the genes must continue to use up substances needed in self-synthesis; and very probably the genes are always producing other substances as by-products of self-synthesis. Every such removal and addition must have a definite influence upon the complexly interrelated reactions of metabolism; and consequently every gene must have some metabolic importance in every cell of the body at every stage of development. No doubt the importance of a given gene is greater in some parts of the body as compared to others. If a gene is to change the pigmentation of the eye, for example, this effect can appear only in such cells as may contain the eye-pigment, or at least in such cells as may contain the precursory substances from which the eye-pigment is to be formed. Thus, each gene may produce several or many effects in the different cells of the organism, depending upon chemical and physical conditions in the different cells; and the destiny of a cell depends not only on its genes, but also on the factors of its environment, and on the intrinsic composition and structure of its own cytoplasm.

Recent studies have made steady progress in determining precisely how specific genes may exert their developmental influence upon the phenotypic characteristics of various organisms, but only two such studies will be mentioned. It has been shown, for example, that dwarfism in mice, which is inherited as a single recessive factor, is mediated through the pituitary gland. The pituitary of a mouse which is homozygous for the "dwarf gene" displays a deficiency of the tissue responsible for the production of the growth hormone (p. 535), and if such a genetically dwarfed individual receives growth hormone injections, it achieves full stature and cannot be distinguished from a genetically large mouse.

Genic effects may also be mediated by specifically identifiable

enzymes, as well as by hormones, as is shown by a study of the inheritance of pigment production in the melanophores of a common fish, the flounder (Fig. 571). Certain flounders are known to lack black pigment in their "melanophores," and this lack, which prevents the fish from changing its shade in accordance with the environment, is determined by a recessive allele of the normal "pigment gene." Accordingly, when heterozygous pigmented flounders are inbred, they produce pigmented and unpigmented offspring in a ratio of 3 : 1. But the significance of this study is revealed by further data. When the melanophores of the non-pigmented individuals are tested, these cells are found to lack one specific oxidizing enzyme, which is present in all normal melanophores. Thus the black pigment, melanin, which is an oxidation product derived from a colorless precursory compound, cannot be formed in the "melanophores" of the non-pigmented fish. From this experiment it may be concluded that the normal "pigment gene" achieves its phenotypic effect in the melanophores of the flounder by determining the production of a specific metabolic enzyme, and a similar action can probably be assigned to many genes in many organisms.

TEST QUESTIONS

1. Explain how and why the known processes of cell division and sexual reproduction convinced biologists, even before they knew anything about genes, that the mechanisms of hereditary transmission must reside in the nuclei of the gametes (and other germ cells).
2. Explain the meaning of the phrase "continuity of the germ cells," exemplifying the discussion by describing the "germ cell cycle" of the frog.
3. How does the prophase of the first maturation (meiotic) division, as it occurs in spermatogenesis (and oögenesis) differ from the prophase of an ordinary (mitotic) division? (At least three differences should be mentioned.)
4. Answer the foregoing question with reference to (a) the metaphase of the first maturation division and (b) the prophase of the second maturation division.

5. Discuss the similarities and differences between spermatogenesis and oögenesis, emphasizing the functional importance of these points of comparison.
6. What is synapsis? When does it occur? What are its genetic consequences?
7. Define and localize: (a) spermatogonia (and oögonia); (b) tetrads; (c) secondary spermatocytes (and oöcytes); (d) spermatids; (e) polar bodies; and (f) ripe ovum.
8. Explain the meaning of the phrase "free assortment of the chromosomes during meiosis," using the sperm produced by a spermatogonium with two pairs of chromosomes (*Aa* and *Bb*) to exemplify the discussion.
9. Make a series of labelled diagrams to show all the stages of maturation in a spermatogonium having two pairs of chromosomes (‖ ‖).
10. Specify all the possible types of gametes which can be formed by each of the following types of spermatogonia:
    a. *AA bb cc;*
    b. *AA Bb Cc;*
    c. *Aa Bb Cc.*
11. All the offspring produced by crossing red four-o'clocks with white ones have pink flowers. What proportions of what flower-colors will be yielded among the direct offspring of each of the following crosses:
    a. pink *X* pink;
    b. pink *X* red;
    c. pink *X* white;
    d. red *X* white?
12. Among the various offspring from the foregoing crosses, indicate those that are (a) homozygous and (b) heterozygous.
13. In summer squashes white fruit (*Y*) is dominant over yellow fruit (*y*). If a squash plant homozygous for white is crossed with one homozygous for yellow, what will the genotype and phenotype ratios be:
    a. if two of the F_1 individuals are inbred;
    b. if one of the F_1 is mated with its white parent;
    c. if one of the F_1 is mated with its yellow parent?
14. In the fruit-fly, long wing (*V*) is dominant over vestigial wing (*v*). What results would be obtained when a heterozygous long-winged fly is crossed with a short-winged individual?

15. What is a back-cross experiment? Why is the back-cross so useful in genetics?
16. Rough-coated guinea pigs crossed to smooth-coated pigs produce only rough-coated F_1 offspring. What results would be obtained:
    a. by inbreeding the F_1 individuals;
    b. by back-crossing one of the F_1 pigs?
17. Twenty-five per cent of the offspring of a certain pair of white sheep are black. What was the genotype of the parents?
18. Explain the statement that hereditary transmission is particulate in character.
19. After four generations, what result would be anticipated if one black sheep (see question 17) were introduced into a herd of pure bred (homozygous) whites:
    a. assuming the heredity to be particulate (as it is);
    b. assuming a "blending type" of heredity (as it is not)?
20. In summer squash, white fruit (Y) is dominant to yellow (y), and flat fruit (R) is dominant to round (r). The selected parents are a plant with white-flat fruit (YY, RR), and a plant with yellow-round fruit. Specify the phenotype and genotypes and their respective ratios:
    a. in the F_1 generation;
    b. in the F_2 generation (inbreed the F_1 plants);
    c. among the offspring obtained by back-crossing one of the F_1 plants.
21. An albino (i.e., pure white) guinea pig with a rough coat is mated with a black one with a smooth coat. The F_1 offspring are all black and rough. What would be the genotype and phenotype ratios in the F_2 generation?
22. A heterozygous black, smooth-haired guinea pig (question 21) is crossed to a white, heterozygous rough-haired mate. What phenotype and genotype ratios would be expected among the direct offspring of this cross?
23. Carefully differentiate between the members of each pair of terms:
    a. the phenotype and the genotype of an individual;
    b. a homozygous and a heterozygous individual;
    c. sex-chromosomes and autosomes;
    d. sex linkage and ordinary linkage;
    e. complete and incomplete linkage.

24. In tomatoes red fruit (Y) is dominant to yellow (y); tallness (D) is dominant to dwarfism (d); the two pairs of genes have their loci in the same pair of chromosomes; and the linkage is complete. What phenotype and genotype ratios would be expected among the direct offspring if both of the parents are red (heterozygous) and tall (heterozygous).

25. Assume that the linkage relation in the parents given in question 24 is $\begin{array}{|c|c} Y & y \\ D & d \end{array}$ and that the cross-over value between the gene pairs is 10%. Specify the gametes of such a parent and indicate the relative abundance of each gamete type.

26. In rabbits black coat (B) is dominant to brown (b); and long hair (S) is dominant to short (s). Derive the phenotype and genotypes which are to be expected when a heterozygous black, heterozygous long-haired pig is crossed to a brown short-haired mate:
   a. assuming that the two gene pairs have their loci in separate pairs of chromosomes;
   b. assuming that the loci are in the same pair of chromosomes and that the linkage is complete.

27. Make a diagram to show how sex is inherited in Drosophila (and in man and many other organisms).

28. What is the basis for referring to the Y-chromosome of Drosophila as a "dummy"?

29. In the fruit-fly, red eye (W) is *sex-linked* and dominant to white eye (w). Specify the distribution of eye color (a) among the males, and (b) among the females, derived from each of the following crosses:
   a. white-eyed female X red-eyed male;
   b. heterozygous red-eyed female X white-eyed male;
   c. heterozygous red-eyed female X red-eyed male.

30. In man, normal vision (B) is dominant to red-green color-blindness (b), and this trait is *sex-linked*. Specify the distribution of normal and defective eyes among the sons and daughters produced by each of the following matings:
   a. color-blind mother and normal father;
   b. heterozygous normal mother and color-blind father;
   c. heterozygous normal mother and normal father.

31. Enumerate the difficulties which have made it difficult to analyze the details of human heredity.

32. If each phenotypic characteristic of the organism is determined by several or many pairs of genes, how is it possible that simple ratios (e.g., 3 : 1 and 1 : 2 : 1) are obtained in the F_2 generation when the inheritance of a given characteristic is studied?
33. Discuss the phenomena of mutation, according to the following topics:
    a. definition of the process;
    b. types of mutation;
    c. frequency of the types;
    d. factors that may modify the frequency;
    e. proof that a mutation cannot represent the mere loss or destruction of a gene;
    f. relation of mutations to evolution.
34. Carefully differentiate between the members of each pair of terms:
    a. genetic and environmental variation;
    b. an aberration and a mutation;
    c. a deficiency and a duplication;
    d. translocation and inversion;
    e. triploidy and tetraploidy;
    f. artificial and natural selection.
35. Discuss the problems of selective breeding, emphasizing particularly:
    a. the general technique;
    b. relation between inbreeding and homozygosity;
    c. the dangers of inbreeding and how these may be overcome;
    d. the practical value of the method;
    e. the limitations of selective breeding.
36. Although all the cells of an embryo are equal as to their genes, all the cells do not remain alike as development proceeds. In general terms, how can this differentiation of the embryonic cells be accounted for?
37. Briefly discuss and *exemplify* each of the following topics:
    a. an experimental technique which demonstrates whether a given part of the embryo is determined or not determined;
    b. an experiment that shows that the presence of one cell (dead or alive) can influence the development of all the other cells in the embryo;
    c. the role of the dorsal lip of the blastopore as an embryonic organizer;

d. the time at which determination occurs in the different parts of a frog embryo;
e. the nature of the organizing influence of the dorsal lip.

38. Explain the basis for regarding the gene:
    a. as a catalyst (enzyme);
    b. as an autocatalyst;
    c. as a single molecule, or at least a unit group of molecules.
39. Discuss briefly the possible ways in which the genes may affect the metabolism and hence the development of a given cell.

FURTHER READINGS

1. *You and Heredity*, by Amram Scheinfeld; New York, 1939.
2. *Multiple Human Births: Twins, Triplets, Quadruplets, and Quintuplets*, by H. H. Newman; New York, 1940.
3. *Experimental Embryology*, by T. H. Morgan; New York, 1927.
4. *An Introduction to Experimental Embryology*, by G. R. DeBeer; New York, 1926.

CHAPTER 26

NATURAL SELECTION; THE ORIGIN OF SPECIES

THE KNOWN facts of reproduction make it certain that the different kinds of plants and animals inhabiting the earth today have descended from species which occupied the earth in previous times; and there are only two alternatives as to the nature of this descent. Either there has been a *fixity of the species*, such that the existing species have *descended without change* from the pre-existing species; or *evolution has occurred*, in the sense that the species have undergone change during the course of their descent from pre-existing forms.

The idea of evolution extends back into ancient times, but Darwin (1859) first succeeded in marshaling the basic evidence. However, it was not until the present century that modern genetics provided the missing clues as to how the known processes of heredity and reproduction inevitably lead to evolution.

Under natural conditions every species of plant and animal is constantly subjected to a process of *selection*. The parents selected to perpetuate each species in every generation are not chosen artificially according to the specifications of mankind, but naturally, according to their *ability to live and reproduce* under the conditions of their particular environment. This process of *natural selection*, as will be apparent shortly, results inevitably from the normal tendency of every organism to multiply at a rate which exceeds the capacity of the environment to support all the offspring of any given species.

Multiplication of Organisms; a Geometrical Progression. Every kind of organism tends to multiply at a characteristic *rate*. Perhaps the highest rate occurs among certain bacteria which, under favorable conditions, will divide once every half hour. At this rate the population would be quadrupled every hour, and in 24 hours the descendants of a single bacterium would number 2^{48} (more than 280 million million), *if they all survived*. A million seeds, or spores, per year is not uncommon for an individual plant; and many invertebrates, and even lower vertebrates like fish, produce more than a million fertilized eggs annually. Higher vertebrates, especially birds and Mammals, do not produce so many eggs, but these animals provide more care for the developing young, so that a larger proportion of the offspring can survive. Probably the slowest multiplication rate is that of the elephant. This animal begins to breed at thirty and continues until ninety, producing an average of six calves during the reproductive period. Even at this exceedingly slow rate, *if every elephant survived*, the descendants of a single pair would number more than 18,000,000 in seven hundred and fifty years; and in three or four centuries, the earth could provide "standing room only, for elephants only."

These facts are summarized by realizing that every kind of organism, whether its multiplication rate be slow or fast, tends to increase in geometrical progression: n, n^2, n^3 . . . etc., where n = the average number of offspring per individual parent per generation, and the exponential numbers designate the sequence of the generations. Graphically this relation is shown by curve *A* in Fig. 329, which is often called the *curve of compound interest, or the growth curve*. In this natural type of multiplication, the rate of increase grows greater and greater as the population increases. Accordingly, if all the offspring survived and reproduced, every species, even those with the slowest natural rates of reproduction, eventually would increase until it covered the earth; and this eventuality would be fulfilled within a relatively short time in relation to terrestrial history.

Limits of Population Increases. Needless to say, plant and animal populations do not actually increase in this manner,

for they are limited by the food supply, and by a number of other *environmental conditions.* This limitation is illustrated by curve *B* in Fig. 329, which shows the actual multiplication of yeast cells in a definitely limited amount of nutrient solution. Initially the actual growth curve follows the theoretical growth

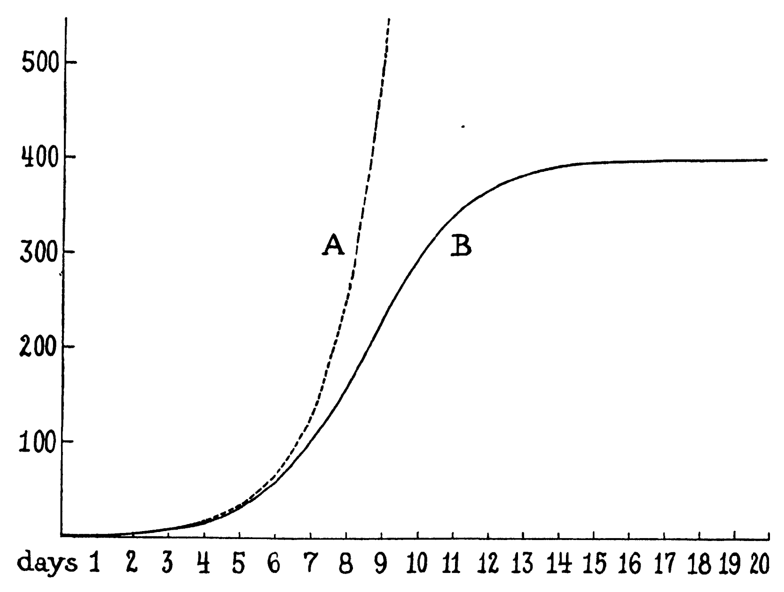


FIG. 329.—Multiplication of yeast cells: abscissae, time in days; ordinates, number of cells (in millions). A, theoretical rate of multiplication with unlimited space and food; B, actual rate of multiplication in a definite limited amount of nutrient solution.

curve very closely, but soon the rate of increase falls off, and finally the number of cells reaches a constant value beyond which there is no further increase. Under comparable conditions, a population of any species behaves similarly, as is shown for Drosophila in Fig. 330, and for man in Fig. 331. In each case the population reaches a constant maximum, under a given set of conditions; and this maximum is attained in a relatively short time, i.e., within a relatively small number of generations. Also the level of this maximum is determined largely by environmental conditions, as may be seen in Fig. 330. After the maximum is reached, a population may fluctuate from year to year or

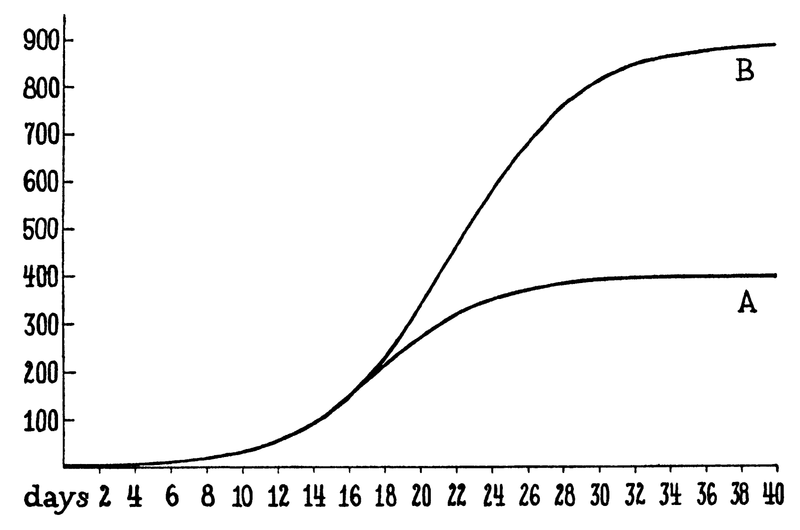


FIG. 330.—Multiplication of Drosophila: A, in a half-pint bottle; B, in a one-pint bottle. Abscissae, time in days; ordinates, number of flies.

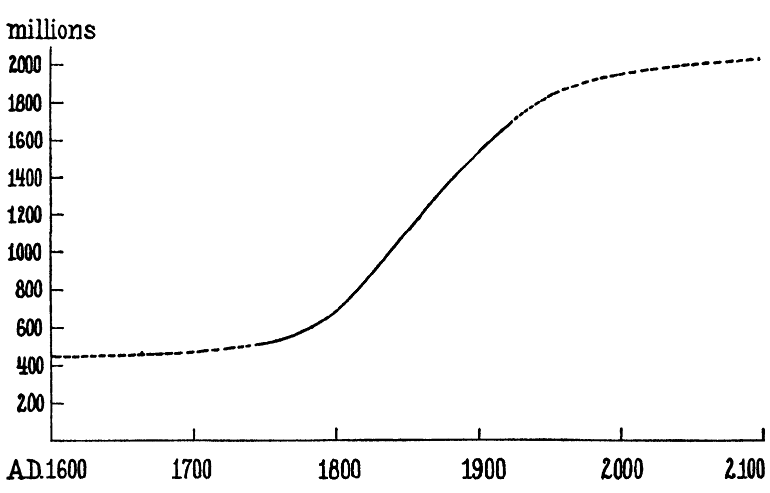


FIG. 331.—Human population of the earth: abscissae, years; ordinates, population in millions. The solid portion of the curve is based on actual data; the dotted portions are purely theoretical, calculated from the equation of the curve. The increase in population during this period, from its previous stationary level, is due to the great change in environmental conditions caused by the Industrial Revolution. The upper, dotted portion of the curve predicts the future population on the assumption that there will be no further great environmental changes—a very doubtful assumption. (Adapted from Pearl.)

—within shorter periods, in rapidly reproducing organisms—in accordance with the food supply and other environmental conditions. But by and large, over any long period, the average level of the population remains quite constant, provided environmental conditions do not undergo a permanent change.

Limitations of the Environment. In general, the principal factor which limits a given population is the *food supply*—using this term in the very broadest sense. Among animals and colorless plants, the fund of organic foods available in the particular habitat is especially important, although water, or oxygen, or other inorganic nutrients may be limiting factors in some environments. But among plants, the primary nutritive factor is apt to be the quantity of accessible *light*, although the available quantity of inorganic foods, such as water, or salts, are sometimes very important.

A number of other environmental factors act directly in determining the population levels of different animals and plants, in addition to having indirect effects upon the food supply. Climatic conditions (heat, cold, wind, ice, snow, fog, etc.) impose definite limits on the extent of territory which can be occupied by a given species; *predaceous* and *parasitic* enemies may prey upon the populations; and a variety of minor factors may assume importance in particular cases. But for any particular species, under unchanging environmental conditions, a balance is reached between its natural tendency to increase and the limiting factors of its particular environment.

Natural Selection. The fact that each species in every generation produces so many offspring that only a fraction can possibly achieve the age of sexual maturity, gives rise to two important questions: What selecting agency scrutinizes the many offspring and chooses the few which are to survive and perpetuate the species; and what characteristics qualify the individuals which are selected?

Generally speaking, organisms which are *fittest to survive and reproduce* under the conditions of their particular environment are automatically selected to perpetuate each species. The selecting agency is the natural environment of each species; and

the main qualification for selection is a *fitness to survive and reproduce* in competition with other organisms which seek to utilize the same environment. Inevitably each organism encounters a ceaseless *struggle for existence*—using this term in the broadest sense—since potentially *unlimited* numbers of each kind of organism are competing for sustenance in a definitely *limited* environment.

The struggle for existence does not imply direct and active combat, except in the case of some predaceous animals. Survival depends more on the organisms' capacity to withstand adverse physical conditions (temperature, light, etc.) and unfavorable conditions (drought, soil fertility, etc.) in the chemical environment. But above all, the struggle is a competition for the *necessities* of life, of which the supply is strictly limited. This aspect of the struggle for existence, indirect and obscure though it frequently may be, reaches a climax of intensity among organisms of the same or closely related species, because such organisms are competing for the *same*, or very similar, necessities.

Take, for example, a group of annual plants sprouting on a limited plot of ground. At first the ground may be thickly covered with a large number of small seedlings; but as the season progresses, the *number* of survivors falls off, while their *size* increases. Finally there are just a few individuals left and these completely occupy the area in which hundreds of seeds originally germinated. Among such plants the struggle is primarily for a "place in the sun," and the struggle is especially keen because light is absolutely essential to every competitor. The seedlings which spread their leaves a little faster and further overshadow the others, cutting off their light and assuring their starvation. But the survivors go on and produce the next year's crop of seeds, whereupon the process is repeated. Thus a selection has been made in the direction of the faster-growing seedlings, and the selecting agency has been the environment. Similarly among animals, the primary selecting factor is very frequently a competition for the limited supply of organic food; and since individuals of the same species have the same food requirements, the struggle is keenest within such a population.

Of course there are wholesale and indiscriminate forces of destruction (storms, floods, glaciers, etc.) which may reduce a population without any regard for the capacity of the individual to *survive* and *reproduce.* Also an individual's survival may hinge upon sheer accident. Some seeds fall on good ground and some on stony ground—due to no virtue of the former or fault of the latter. But over and above such non-selective eliminations, *speaking in terms of the average,* the individuals of a species which are most healthy, vigorous, capable of securing food, escaping or protecting themselves from enemies, resistant to disease and unfavorable weather, and so forth and so forth—in short—those which are *fittest to survive and reproduce* under the given conditions—are most likely to be the perpetuators of the species. Thus variations—or more particularly variations of the heritable type—play a very definite role in survival by providing the material upon which the environment exerts its selective action.

Natural selection differs from *artificial selection* not only as regards the criteria by which the surviving individuals are chosen, but also as to the *time element.* Progress ceases in an artificially selected line when all genes favorable to the chosen characteristics have been collected in a group of pure-bred individuals. This is because man does not have *time* to wait for "lucky" mutations in a desired direction. But natural selection has no such limitation. Natural selection has "all the time there is." Generation after generation, century after century, millennium after millennium, the struggle for existence goes on, selecting the fittest and eliminating the less fit. A great majority of mutations, probably, are soon eliminated because they are unfavorable; and many mutations may be indifferent as to their survival value. But some favorable mutations—especially of the slight type—are bound to appear periodically. Even favorable mutations may accidentally be eliminated; but *on the average* if a mutation gives any advantage to its possessors, the mutant individuals will have a greater chance than the non-mutant individuals of surviving and transmitting the new trait to their descendants; and in the next generation, the mutants, in turn, will

be similarly favored in the struggle for existence. In the long run, therefore, every mutation which is favorable to survival or reproduction stands a good chance of being permanently incorporated in the genetic constitution of the species.

Artificial and natural selection differ, broadly, in that artificial selection operates chiefly by the more rapid but limited method of selecting favorable *recombinations* of existing genes; while natural selection operates by the slower but potentially unlimited method of selecting favorable new *mutations*. To some extent both methods operate in both cases, since both the artificial and the natural processes actually select the surviving parents on the basis of their phenotypic characteristics, regardless of how these arose. The great difference lies in the time factor; artificial selection has operated for only a few centuries, at most; but natural selection has gone on for millions of years. Natural selection proceeds in a bungling, haphazard, hit-or-miss fashion, and therefore it is very slow. But given an infinity of time, even such a slow and halting process can produce tremendous results —as is witnessed by the great diversity of living forms inhabiting our earth today.

Adaptation. Under natural selection each species must attain a fitness to survive and reproduce; or otherwise it faces extinction. Consequently it is not surprising to find many qualities of "fitness," or *adaptations*, in all kinds of living things.

The most obvious adaptations have to do with the *external features* of the organism, taken in relation to its particular environment. Among animals, for example, the coloration tends to be inconspicuous in relation to the background of a particular habitat; or the mouth-parts are shaped for handling a certain kind of food; or the appendages are fitted for locomotion on land, in the sea or in the air—and so forth. And among plants: the roots, stems, leaves and other organs are variously modified according to conditions in different localities. Many of these obvious *external adaptations* are important in relation to survival, but *internal adaptations*, which are not so obvious, are probably even more important.

Each organism consists of an intricate system of interacting

components, ranging from ultramicroscopic units such as enzymes and substrates, up to the macroscopic organs of the body. Internal adaptation embraces the sum total of these parts and their interactions; and internal adaptation assumes a paramount, though frequently hidden, importance in survival. If a mutation unbalances any of the delicate internal functions, the organism cannot survive at all, regardless of the particular environment. Therefore, the only mutations that can possibly lead to a greater degree of external adaptation are those which also have a neutral or advantageous effect upon internal adaptation. Likewise, some mutations may be perpetuated, if they have a favorable effect upon the internal adaptation of the species, even though the more obvious external phenotypic effects of such mutations are partially disadvantageous to survival. Such internal effects seldom involve any visible changes of structure; but presumably they involve changes, however slight, in the chemical composition, or ultramicroscopic structure, of the tissues. They are usually referred to rather vaguely as changes in the "viability" or "fertility" of the stock. But despite the fact that they are invisible and very difficult to study, these internal variations are most important. Natural selection must—and demonstrably does—deal with many such intangible characteristics.

External adaptations include all the visible characteristics of the individual which fit it to survive and reproduce in its own *particular* environment. The shaping of all external structures with reference to food-getting, respiration, self-defense, protection, reproduction, and so forth—all fall into the category of external adaptations. But even more important, perhaps, is the external *behavior* of the organism: its responses to particular environmental situations. Natural selection has preserved individuals and races whose responses are useful—to themselves, of course—and has eliminated those whose behavior was less favorable to survival. Accordingly, it is found that most unconditioned responses—tropisms, instincts, etc.—are strikingly adapted to the conditions of the natural habitat of the particular organism.

The environment of any organism is an extremely complex

set of conditions. It includes not only the many physical and chemical conditions of inanimate nature, but also the multitude of *living* things with which each organism comes into various kinds of relations—predatory, parasitic, symbiotic, competitive, cooperative and so forth. So complex are these interrelations and so delicate is the balance between the processes of multiplication and destruction in any given species, that the very slightest factor may tip the scales, determining whether the individual, the race, or the species shall perish or survive. Without most careful study, therefore, it is very risky to judge that a particular characteristic has no survival value for the organism. On the other hand, it is not necessary to assume that every visible characteristic—such as the humps of the camel, the bumps of the wart-hog, or any other peculiarity of form, color, or habit—must necessarily have some adaptative significance. In many cases such features are merely incidental effects of genes which have less obvious but more important effects upon the internal functions of the organism.

Stability of the Species. Since most mutations are not favorable, natural selection acts to preserve a high degree of *uniformity* in each species—by eliminating a majority of these heritable changes as fast as they appear. Wild species display less variability than domesticated animals and plants. In the case of domesticated species, man has interrupted the natural struggle for existence and has artificially preserved a number of less viable variants which, under natural conditions, could not have survived in competition with their wild-type relatives. But even wild species are genetically heterogeneous for many genes with relatively slight phenotypic effects, because natural selection tolerates a number of *slight mutations*, even though it almost always eliminates the larger ones.

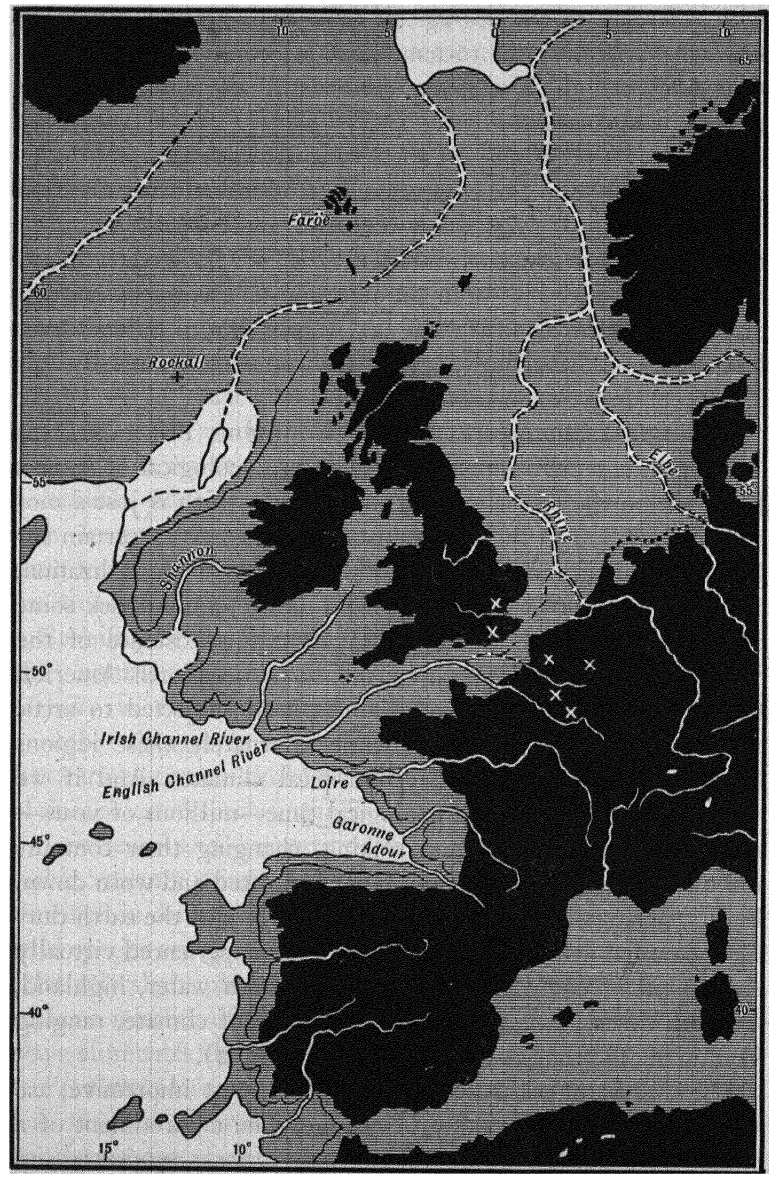
Provided the environment does not change, any species which has occupied a particular habitat for a great many generations becomes about as well adapted to conditions as its inherent genetic nature will permit. In other words, after a long time, the possibility of new favorable mutations becomes rather small. Under these conditions, therefore, most species are fairly stable

with reference to the *average* of their characteristics, although seasonal variations, due to temporary selections of more favorable combinations of existing genes, still allow for a certain degree of fluctuation.

However, the stability of species cannot withstand any long-enduring change in the environment. Considered over a period of a few years, or even a few centuries, most *natural* environments—that is to say, environments which are not greatly modified by man's activities—remain quite constant as to the average of the cyclic changes of the day and season. But considered over longer periods, practically every environment repeatedly has undergone great changes.

Geological Changes in the Environment. The most obvious long-range environmental changes are geological in nature. Even within the period of human history—which is just a moment in relation to the whole history of the earth—certain regions of Asia which once supported a flourishing civilization, have become deserts virtually devoid of life. Going back some few thousand years further—still within the existence of the human species—vast regions of the earth, in North America, Europe and Asia, have several times been subjected to arctic conditions—due to glaciation—while alternately these regions have experienced tropical or subtropical climates. And if we look still further back into geological time—millions of years—we see continents rising and sinking, changing their contours and connections; and mountain ranges elevated and worn down. In fact, practically every region on the surface of the earth during the period in which life has existed, has experienced virtually every kind of environment: salt water, fresh water, highland, lowland, desert, swamp; under every type of climate, ranging from arctic to tropical temperatures (Fig. 332).

These great physical fluctuations, while most impressive, are not the only important kind of change. The environment of a species also consists of its relations to *other organisms:* and whenever a species invades new territory, increases or decreases in numbers, or changes its mode of life in any respect—quite a number of other organisms are likely to be affected directly or



From Osborn, *Men of the Old Stone Age,* by permission of Charles Scribner's Sons

FIG. 332.—Land areas of Western Europe in the 3rd interglacial stage. Present areas, in black; former areas, lighter.

indirectly. Consequently each significant modification of the inanimate environment is always attended by many changes in the animate environment of all species in the affected region.

Origin and Extinction of Species. Every long-range change in the climate and other environmental conditions has, owing to these many factors, many effects upon the species of the region: some species decline or even become extinct; other species increase their numbers and extend their range. Slight variations which were barely tolerated by the previous environment may assume real survival value under the changed conditions—so that these particular variants will displace the species types which dominated under the old conditions.

When an environmental change is favorable to a given species, its population will increase; and during this period of less rigorous competition a larger proportion and a wider variety of offspring will be tolerated for a number of generations. By chance some of the new variants may be adapted to slightly different environments, which enables the species to extend its geographical or its ecological range. When, however, environmental conditions become harder for the species, many of its less fit or weaker varieties may be wiped out, leaving just a few sharply distinct varieties—or incipient new species. In good times, generally speaking, a species tends to increase in number and variety; and greatly extends its range of territory. Then when hard times come, the species may become extinct over large areas of its former territory, leaving a few exceptionally fit and perhaps very sharply different varieties, each quite *isolated* from the others, in different parts of the former range. This factor of *isolation,* whether due to *geographical separation* or to other conditions, is very important in the origin of species. Whenever two varieties are isolated and prevented from intercrossing for many generations, the mutations of one group cannot spread over into the other. Continually and gradually the stocks become very different, and finally a genetic incompatibility will result. Thus, when interbreeding becomes impossible, the isolation is complete, and the further evolution of the stocks must be as separate species.

Natural selection, acting upon a group of closely related organisms, over a long period of time, inevitably produces results such as are shown in Fig. 333. The letters at the left represent a group of seven closely related species or—starting one step earlier—seven isolated varieties of a single species; and the intervals between the successive vertical lines in the figure may be taken to indicate approximately a thousand generations. Each species continues to produce new mutant varieties, and although most of these varieties are quickly eliminated by natural selection, some persist for longer periods. Thus, in the course of ten thousand generations, the several original species may meet with totally different fates, as may be seen in the figure. One species has given rise to several new forms, while the original species has disappeared; in another case, the original species has persisted without changing, while all its offshoots have perished; in a third species, both the parent form and some of its offshoots have survived; and lastly, the other species of the original group have become entirely extinct, leaving no descendants, after surviving for a shorter or a longer period. At the end of ten thousand generations, the number of distinct forms—species or varieties—may be no greater than originally, although a much greater number of forms has meanwhile appeared and disappeared. The surviving species, also, are related more or less closely to each other, because of their method of origin.

Thus the original group of species has given rise to a number of more sharply separated—or more distantly related—species, which tend to assemble themselves, according to relationship, into several larger groups. Perhaps these larger groups are already sufficiently distinct to be considered as separate *genera*, or perhaps the separative action of a greater number of generations will be required before this point is reached. In any event, natural selection, operating through ages of time, continues the fateful processes of diversification and extinction. It creates new species, not abruptly and *de novo*, but gradually, from preexisting species. And as a result of the relentless processes of natural selection, working in conjunction with an ever-changing environment, man finds himself upon this earth today—together

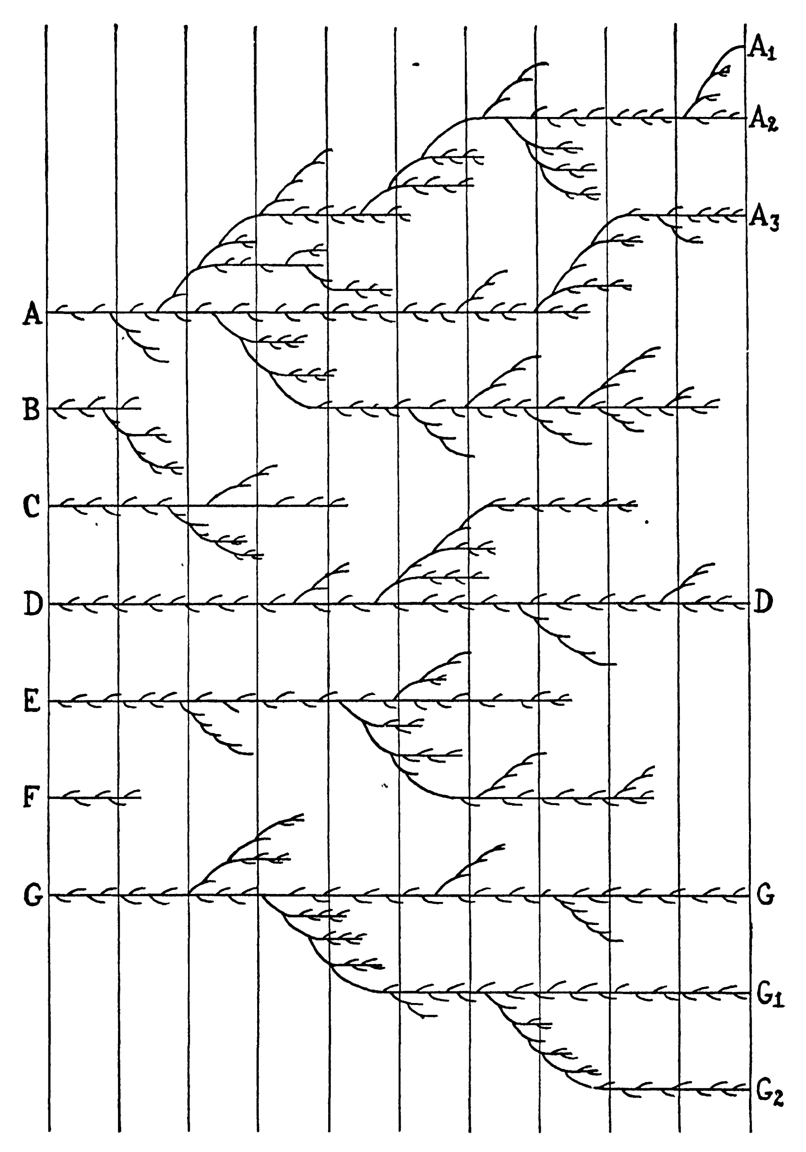


FIG. 333.—Origin and extinction of varieties and species by natural selection. The horizontal dimension represents time (i.e., the succession of generations), the vertical dimension variation. The very short branches represent the numerous mutations which are quickly eliminated by natural selection, the longer branches those which persist for longer periods. (Adapted from Darwin.)

with a tremendous variety of other living species, all variously adapted to current environmental conditions, and all variously interrelated as to their origins. Also man finds within the earth itself, the tell-tale remnants of a vastly greater number of plant and animal species, which have become extinct in past ages (Chap. 27).

Natural Selection and Modern Genetics. The origin of species by natural selection was first explained by Darwin in 1859; but at that time very little was known about the laws and mechanisms of heredity and variations. Darwin based his conclusions on the unquestionable facts: that all organisms do vary; that *some* variations are heritable; and that large variations are generally less viable than slighter ones. Since Darwin's time—chiefly in the last forty years—the mechanisms of heredity have been thoroughly clarified and much has been learned about the origin and nature of variations. Prior to these developments, the chief objections to the theory of natural selection were: that the theory did not account for the appearance of many apparently useless features in different organisms; and that variations, especially slight ones, would be lost by "dilution" when the variant individuals continued to interbreed with the more numerous members of the species not possessing the particular variations in question.

Both of these objections are eliminated completely by an understanding of genetic principles. The visible differences between closely related species are not necessarily of critical importance in survival, since frequently these visible characteristics are incidental effects of the *same genes* which produce invisible effects having great survival value. Furthermore, the idea of "dilution" has proved to be altogether fallacious: when mutant individuals continue to cross with the original type, the processes of *particulate inheritance* guarantee a distribution of the mutant gene throughout the whole population without any alteration of the new gene throughout successive generations.

Imperfections in an organism, or the possession of features which *seem* to reduce its fitness in relation to its particular environment, are not difficult to understand, if the limitations of

natural selection are carefully considered. Natural selection cannot *produce* favorable variations, it can only preserve them, if *by chance*, they do arise. The possibilities of favorable variations are strictly limited by the existing genetic constitution of the particular organism: the possible ways in which its various genes can undergo change without disrupting the delicate balance of existing functions within the organism. Thus natural selection is restricted mainly to small changes, and must therefore work very slowly. Moreover, since heredity is particulate in nature, each new gene must be selected or discarded *as a whole*. This means that disadvantageous phenotypic effects may be carried along with advantageous ones, if the former are less important in survival. The survival of a particular individual or race is determined, not by the perfection of any one characteristic, but by the aggregate fitness of all its characteristics. The survivors in the struggles for existence need not be perfectly adapted—but merely sufficiently adapted to "get by" until they produce an adequate number of offspring. Each organism is "made-over" and "patched-up" to meet its new environment, each time there is a swing in the mighty pendulum of geologic time. Consequently each plant and animal may possess a number of useless or even definitely harmful characteristics, resulting from the sorting out of innumerable *chance* variations. Survival does not require perfect adaptation. It merely demands that the individual be as well adapted as its competitors—all of which have also been produced by the same method.

Lamarckism: A Disproved Theory of Evolution. Prior to Darwin, evolution had many proponents; and several theories were advanced as to how evolution has wrought its slow but tremendous changes in the species. These theories rested mainly on the supposition that *all* variations in the characteristics of the organism are transmitted to the offspring, a weakness which is well exemplified by the theory of Lamarck. This work on evolution was published in 1809; and Lamarck's contribution was important, despite the fact that the central theme—as to the mechanism of evolutionary change—is not tenable in the light of modern genetics.

According to the Lamarckian view, each organism is molded by its contacts with the environment, and these *acquired characteristics* are subsequently transmitted to the offspring. In other words, Lamarck held that the environment *produces* heritable variations which fit each organism to cope with the particular conditions of its habitat; and that the perpetuation of these acquired characters produced changes in the species in accordance with the geological changes of the environment.

Lamarck's ideas had great appeal in the early part of the nineteenth century, and the theory was not abandoned until it was proved beyond all doubt that *acquired characteristics are not inherited.* The environment, to be sure, is very effective in determining the qualities of every individual, but these *modifications* are localized in the *somatic tissues of the body*, and the *germ cells* remain unchanged.

To exemplify the non-inheritance of acquired characters, we will consider a homozygous stock of garden peas. When grown in well-watered soil these plants develop a moderately extensive root system. But if the same plants are grown in unusually dry soil, the roots become distinctly deeper and broader up to a limit which is determined by the genetic potentiality of the stock. In fact, so long as the same relatively dry environment is maintained, the well-developed root system will continue to appear, generation after generation; but no *progressive* improvement will occur. Moreover, when the seedlings of this stock are finally restored to normal conditions, no permanent change in the root system can be observed. The dry environment has brought out the utmost of root development in the given stock; but the environment has not been effective in molding the genetic constitution of the stock in the direction of greater fitness to cope with the dry condition. Aside from the remote possibility that a favorable mutation might occur during the period of the study, the plant experimentalist has no hope of improving any homozygous stock as a result of directive influences from the environment. The environment, to put it more technically, is able to effect a limited improvement in the developmental performance of the group of genes determining the

root system of the stock, but the environment has not been able to produce any measurable change in the intrinsic nature of these genes.

Similarly a great many experiments have been performed on other organisms using a variety of adverse environmental conditions, such as chronic alcoholism. One inbred stock of white rats were daily subjected to extreme alcoholism from the time of weaning until death, for more than ten generations. During this period of extreme debauchery, there were amongst the litters a very high proportion of feeble, stunted individuals; but the offspring of all such rats were restored to a full measure of growth and vigor as soon as they were taken off the alcoholic treatment. The alcohol did not alter the genic complex of the treated animals, and consequently none of the adverse *acquired characteristics* found a permanent place in the heritable constitution of the race.

Lamarck's theory laid great stress on the question of *use and disuse* of the various organs of the species. The horse, for example, was considered to have arisen from a slower running form which inhabited the open plains, where a constant exercise of speed was essential in the avoidance of carnivorous enemies. Accordingly, improvements in the skeletal and muscular structures of the legs were thought to have occurred gradually as a result of the excessive use of these organs demanded by the environmental conditions. And conversely, blind species, which are found inhabiting deep dark caves, were thought to have arisen as a result of a gradual degeneration of the eyes, due to many generations of disuse.

Two main fallacies of the use and disuse theory are: (1) all experiments designed to prove an inheritance of environmentally induced changes in somatic structures have been unsuccessful; and (2) although certain factors in the environment, such as heat and short-wave radiations, may accelerate the appearance of mutations—these heritable variations are random and are not directed by the environment toward a greater fitness of the variant with reference to its habitat. One such experiment involved the rearing of fruit-flies in total darkness for more than 60 genera-

tions—an equivalent of many centuries in human history. When this experiment was finished and the flies at long last were restored to light, no changes could be found, either in the structure of eyes or in the responses of the flies to light. Similarly, the custom of binding the feet of high-caste Chinese women—which makes it virtually impossible for these individuals to walk—has had no heritable effect upon the foot dimensions of the race, even after many centuries. Likewise, many sorts of mutilations, including the surgical removal of certain organs, have been adhered to religiously by various peoples since the dawn of human societies—without leaving the slightest mark upon the genetic constitution of any race. These environmentally induced modifications do not penetrate to the level of the germ cells of the species; and no change can plav a significant role in evolution unless it involves the genes of the germ cells. Thus it can be said that the environment has no directive influence upon germ cell mutations, except that the environment eliminates such mutations as may decrease and selects such mutations as may increase the general fitness of the species.

The impact of modern genetics upon the theory of natural selection has thus been to clarify and strengthen it, without essentially modifying this theory as developed by Darwin. The known laws of variations and heredity operate by providing material which is sifted and screened by natural selection. These somewhat blind and haphazard processes logically account for the origin of the species of animals and plants which exist today; and modern science can see no other alternative.

TEST QUESTIONS

1. Calculate the number of offspring that would be derived from a single pair of cats in ten generations, assuming that the average number of kittens produced in each generation were four and that all the offspring were to survive and reproduce. Plot the theoretical growth curve of this population of cats.
2. A certain troutless pool, in which the food supply can sustain no more than 100,000 trout, is seeded with 5 pairs of finger-

lings. Assuming that each pair produced 100 offspring annually, what percentage of the offspring can survive:

a. in the first year;
b. in the second year;
c. in the third year;
d. in each succeeding year?

3. Predict ten factors in the *inanimate* environment that might exert a selective action upon the population of trout in the foregoing pool, and explain the type of variation that would be probably favored by each of the given factors.
4. Consider Question 3 in terms of several possible factors in the *animate* environment of the pool.
5. To what extent does Question 3 illustrate:
   a. the "struggle for existence";
   b. the "survival of the fittest";
   c. natural selection generally?
6. Point out the essential similarities and differences between natural and artificial selection.
7. Differentiate between external and internal adaptations.
8. Explain how the external adaptations of fish generally equip these animals for life in the aquatic environment.
9. Explain how the external adaptations of a particular species of fish may equip it for life in a particular kind of aquatic environment (e.g., in a particular pool).
10. In terms of some particular animal explain how some essential internal adaptation may be responsible for perpetuating some neutral or disadvantageous characteristics in the species.
11. To what extent has the environment of the different areas of the earth (e.g., New York State) undergone drastic change during the ages of prehistoric time?
12. In general, how is a species affected in number, diversity of variation, and area of habitation: (a) during periods when the environment is especially favorable; and (b) during periods when the environment is especially unfavorable? Explain.
13. Explain why isolation is a very important factor in determining the origin of new species. Explain several ways in which two or more varieties of a species may become isolated from each other.
14. How may isolation from competitors affect the perpetuation of a given species (e.g., the various monotremes and marsupials (p. 509) of Australia)?

15. Differentiate between genetic variations and environmental variations (modifications). Cite five examples to illustrate how a given animal (e.g., man) and a given plant (e.g., a fruit tree) is susceptible to the modifying influence of environmental factors.
16. Summarize the evidence which strongly supports the view that all environmental modifications are non-inheritable (choose at least two specific examples).
17. Carefully explain the Lamarckian concepts of the mechanism of evolutionary change. What has been the basis for discarding these concepts?
18. Carefully summarize the modern concepts as to the mechanism of evolutionary change.

FURTHER READINGS

1. *The Origin of Species*, by Charles Darwin; London, 1859.
2. *The Scientific Basis of Evolution*, by T. H. Morgan; New York, 1935.
3. *What Evolution Is*, by G. H. Parker; Cambridge (Mass.), 1925.
4. *The Causes of Evolution*, by J. B. S. Haldane; New York, 1932.

CHAPTER 27

THE CONSEQUENCES OF EVOLUTION

EVERY mutation or other heritable change, if it becomes established in a species, either by natural or artificial selection, represents a definite evolutionary step; and in this sense evolution is directly demonstrable by experiment. But the conclusion that all existing species have originated by similar processes occurring in past ages cannot—in the nature of the case—be subjected to *direct* proof. In accordance with the scientific principle of the *uniformity of nature*, however, evolution represents a logically predictable consequence of known forces and processes. Geology and physics provide good evidence (p. 726) that organisms have lived on earth for more than *three billion years*, while the environment, aside from large-scale fluctuations in local conditions, has not undergone great change. It may be assumed, therefore, that variation and selection have operated during these past ages at much the same rate as they do today; and this rate, operating through this expanse of time, seems ample to account for the evolution of the great diversity of existing species. Moreover, evolution has left indelible imprints upon many structural and functional characteristics in every organism; and the crust of the earth contains the fossilized remnants of many kinds of pre-existing organisms. Thus an accumulation of evidence from many sources impels the scientific mind to accept the evolutionary viewpoint. Organic evolution does not necessarily demand that all existing organisms have arisen from a *single* primitive ancestral form; but the bulk of evidence indicates that early primordial life was very simple, and did not consist of any great diversity of forms.

Evolution has left its mark upon every phase of biology, as has been noted in many places throughout the earlier chapters. In summary, therefore, the consequences of evolution will be considered very briefly, under the topics of: *classification, comparative anatomy, embryology, biochemistry,* and *paleontology* (the study of fossils).

Evolutionary Basis of Classification. According to their similarities and differences, organisms have been classified into groups and subgroups, i.e., in the various phyla, classes, orders and so forth—of the plant and animal kingdoms (Appendix I). This classification is not an arbitrary system, as is witnessed by the fact that all organisms in a given group, however large this group may be, resemble each other not merely as to one characteristic, but as to many. Originally the classification was laid out on the basis of the gross structures mutually possessed by members of each group, but subsequent study has usually revealed many other resemblances—as to developmental, biochemical and physiological features, which were entirely unknown to the biologists who first devised the classification. Such facts very clearly indicate that there are real, natural relationships underlying the classification system. In fact, the main intent of classification is to group organisms according to their genetic relationships with other organisms. On the average, those organisms most closely related by descent will mutually possess the greatest number of similar or identical genes; and organisms possessing the greatest common fund of similar genes will resemble each other most closely as to their phenotypic characteristics. Of course there are exceptions to these general rules: identical genes may arise independently even in species of fairly distant relationship; and, on occasion, the phenotypic effects of one set of genes may simulate quite closely the effects of a different set of genes. Therefore, resemblance in one or a few characteristics is not a safe criterion of genetic relationship. But it is not probable that such coincidences should occur frequently, and the more characteristics a group of organisms possess in common, the greater is the certainty that these resemblances are due to common genes derived from a common an-

cestry. And whenever it is possible to test this question by breeding experiments, organisms which appear to be most closely related on the basis of their phenotypic features, are in fact generally found to possess the greatest number of common genes. Actually the modern system of classification considerably antedates the methods of modern genetics; but the criteria which were used in establishing the classification of organisms have proved, on the whole, to be quite valid.

It is possible to subdivide existing species into well-defined groups, only because a large proportion of intermediate organisms have become *extinct*. If every species and subspecies that ever lived were still alive today, there would be no definable groups, but a continuous series of intermediate forms connecting every type of organism with every other type, by insensibly small degrees of difference. Classification depends in a large measure upon the accidents of extinction, and thus we do not find a neat symmetrical scheme, but rather a confusing system of large, small, well-defined, ill-defined, remotely different and closely similar species, genera, families, orders, classes and phyla, making up both the plant and animal kingdoms. Existing species are frequently and aptly compared to the surviving twigs of a buried tree, of which the main limbs and branches have decayed and disappeared. Classification must seek to assign each twig to the proper branch and subbranch—from which it initially originated. In many cases this task is simplified by the uncovering of a few more or less imperfect remnants (fossils) of the former connections; but under the circumstances it is not surprising that there are many uncertainties and differences of opinion. In some cases there are so many intermediate forms between two different groups, that the line of separation must necessarily be altogether arbitrary—as is the case of the line which separates the animal and plant kingdoms. In other cases the opposite difficulty arises: so much extinction has occurred, that certain small groups of species are left, isolated with no obvious relations to any other larger group—as in the case of several invertebrate classes (Nemertines, Rotifers, p. 742). All in all, therefore, classification, or *taxonomy*, is a very difficult

science, fraught with uncertainty and controversy. But experience has shown that this natural system is very useful. In giving the phylum, or class, or other lesser category of any animal or plant, the name of the group immediately specifies that this organism possesses a long list of structural, functional and developmental characteristics, in common with all other members of the same group.

Comparative Anatomy in Relation to Evolution. Each large group of organisms, such as the phyla and classes of the animal and plant kingdoms, displays a fundamental architectural plan of body structure which underlies the diverse specializations of the different body parts. Invariably all the members of such a group possess a number of *homologous* organs which display unmistakable similarities of structure and development, although the particular organ in the different species may be adapted to totally different functions. Generally speaking, the *differences* between homologous organs show an adaptative relationship to differences in the environments of the several species—as would be expected as a result of natural selection. But the *similarities* between homologous organs seem to have no logical explanation, except in terms of genetic relationship.

To exemplify *homology*, let us take the skeletal system of vertebrate animals; or more particularly the bony structure of the fore-limbs throughout the vertebrate group. Regardless of whether the fore-limb is adapted for walking, swimming, flying or other special function, the same grouping of homologous bones can easily be recognized in any vertebrate—as is shown in Fig. 334. This does not mean that such a skeletal structure is ideally suited for all these purposes. The walking, swimming and flying appendages of insects are just as well adapted to each of these same functions; although insect appendages display a totally different plan of structure. The *differences* between the fore-limbs of various vertebrates are obviously correlated with their different environments and functions—while their underlying *similarities*—as to the form and arrangement of the homologous bones and muscles—must be ascribed to the fact that

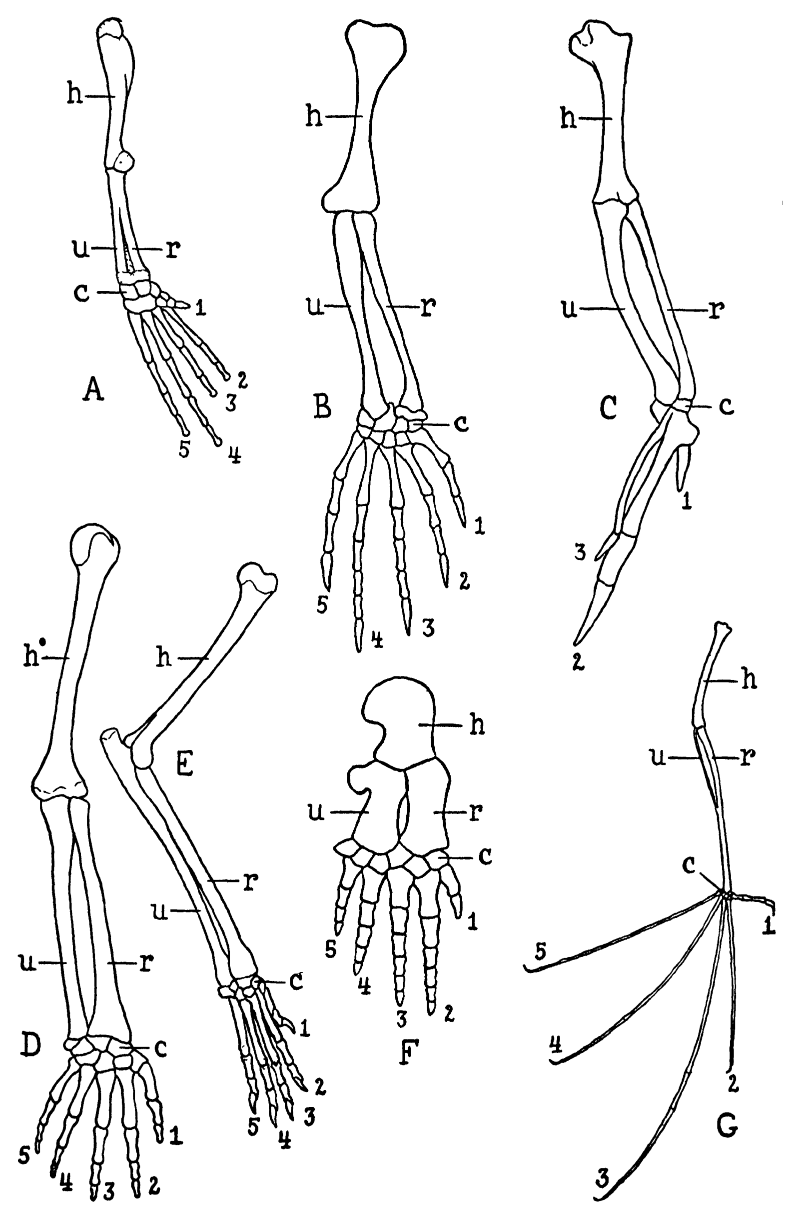


FIG. 334.—Homologous bones of the fore-limbs of various vertebrates: A, frog; B, lizard; C, bird; D, man; E, cat; F, whale; G, bat. h, humerus; r, radius; u, ulna; c, carpus; 1-5, digits.

all vertebrates are genetically related to each other more closely than to other animals.

Similarly the whole skeletal system, as well as all the muscles, nerves, sensory organs, digestive organs, reproductive structures, etc., of vertebrate animals display innumerable homologies of structure and development. The same general architectural plan can be seen in the body structure of every vertebrate, and no other group of animals conforms to this particular plan. Variation and selection have modified the plan to fit a wide variety of special environmental conditions in a wide variety of species; but the plan itself remains to testify as to the common inheritance which all vertebrates have received from a common ancestral stock.

Vestigial Organs. Some organs in every species appear to be quite useless and degenerate as compared to homologous structures in related species; and such *vestigial organs* are by no means rare. The complete list of vestigial structures in the human body, for example, probably numbers more than a hundred; and the list includes a number of familiar structures, such as the *vermiform appendix*, the coccyx (tail vertebrae, Fig. 182), the nictitating membrane of the eye, and the small muscles which can be trained to "move the ears." Moreover, comparable numbers of vestigial organs are found in other groups of animals and plants—in proportion to the complexity of their structure, and to the care with which they have been studied.

A vestigial organ is presumed to represent the surviving remnant of an organ or structure which was well-developed and functional in some ancestral species. Or to state the matter more specifically, the vestigial organ is the product of a surviving group of genes derived from genes which previously governed the development of some useful organ in an ancestral species. As a general rule, organs which become useless to a species as a result of changes in its habits and environment, tend, in the course of evolution, to degenerate in size and refinement of structure. The eyes, for example, of many cave-dwelling species of crustaceans, fishes and amphibia, are blind and degenerate, although these non-functional eyes still show a similarity of

structure and development to the functional eyes of closely related daylight-dwelling species. Given adequate time such an evolutionary degeneration of useless organs would seem to be inevitable on the basis of mutation and natural selection. Mutations are random and prone to decrease, rather than increase, the size and perfection of the affected parts. So long as the organ in question has value in the survival of the species, such detrimental mutations are quickly eliminated by natural selection. But if a structure has become non-essential to survival, detrimental mutations will tend to accumulate and spread throughout the population. In fact the displacement of a useless organ will be accelerated by natural selection, because the whole organ would require a greater share of the organism's food supply—compared to its partly degenerate counterpart. Natural selection tends to reduce and eliminate useless structures, although a long-enduring persistence may occur as a result of the random nature of the degenerative changes, or as a result of hidden effects of the persistent genes, which may be favorable in relation to the internal adaptation of the species (p. 694).

Embryology and Evolution. In any group of related species the embryonic stages tend to resemble each other much more closely than the adults (Fig. 335)—for reasons that are not very difficult to find. In the earlier embryonic stages, all organisms are relatively simple as to their gross structure, so that little opportunity is afforded for drastic differences to appear. Moreover, many genes produce their phenotypic effects relatively late in embryonic development, so that differences induced by these genes are added to the differential effects of earlier-acting genes. Thus in some cases the embryonic stages of a species reveal genetic relationships that would scarcely be suspected on the basis of adult structure. This is particularly true of parasitic or otherwise degenerate forms in which the adults lose many of the characteristics of the group to which they belong. Frequently the mutations responsible for these losses have their main effects relatively late in development, so that the early development of the species displays an unmasked resemblance to the embryos of the other members of the group.

In some cases, however, the *larvae* of related animals do *not* resemble each other more closely than the adults, but such larval differences usually show a distinct adaptive relation to the habitat in which the larvae live. Highly distinctive larvae are particularly characteristic of insects and other forms which spend a considerable proportion of their life span in the larval

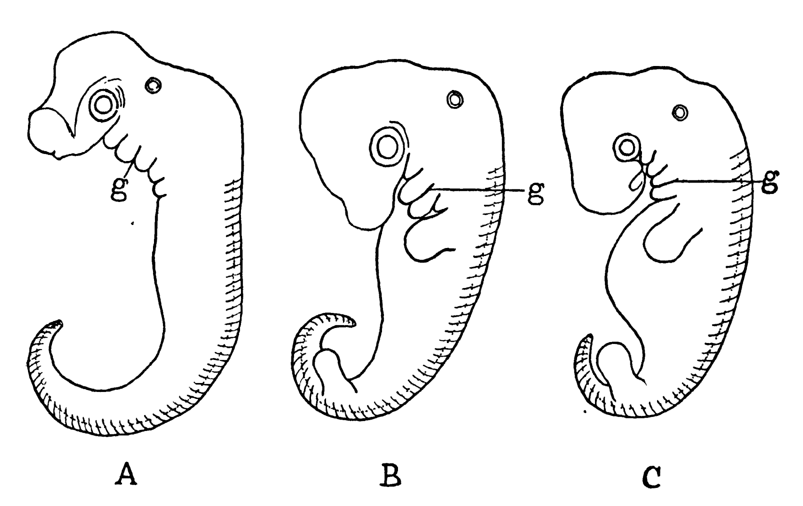


FIG. 335.—During early development the embryos of various vertebrates are strikingly similar: A, fish (shark); B, bird (fowl); C, Mammal (man). g, gill-slits.

stage. In such cases, apparently, natural selection has acted to preserve a number of early-acting mutations which have survival significance during the larval stages. Later in development many of these special larval adaptations are lost, for during metamorphosis, the structures of the adult are derived from less-specialized parts of the larva. In short, differences between related species may appear at any stage of development—embryonic, larval, or adult—although it is undeniably true that genetic relationships are apt to be plainer in the earlier stages of development.

Higher animals, due to the greater complexity of their mature structure, tend to differ more drastically from their respective embryos than do their lower, or simpler, relatives. For

this reason, the embryonic stages of higher animals are apt to exhibit striking resemblances to the adult stages of lower species. For instance, the embryos of all vertebrates develop gill-slits in the pharynx (Fig. 335); and in lower vertebrates (fish) these gill-slits remain as functional respiratory channels in the adult species. But in the higher air-breathing vertebrates, the gill-slits are closed, except for the first pair, which becomes modified to form the Eustachian tubes (p. 336). Apparently the genes responsible for the development of gill-slits in the ancestral vertebrate stock have persisted, while other genes, which decree the closing of these channels, exert their developmental effects later in the embryonic period. In a sense, therefore, gill-slits are to be regarded as embryonic vestigial structures.

Biologists of the eighteenth and nineteenth centuries were deeply impressed by the resemblance of early embryonic stages of higher animals to the adult stages of lower members of the same class or phylem. In fact these observations formed the basis of the *theory of recapitulation*, which was accepted very widely. Briefly, the recapitulation theory held that every species, in passing through its embryonic stages, repeats the evolutionary stages by which the species has reached its present status. Without question the recapitulation theory served a useful purpose in emphasizing the general similarity between embryonic development and evolutionary development. All multicellular animals do in fact revert to the unicellular condition at conception; and the blastula, gastrula, and other generalized stages of embryonic development do tend to parallel the early steps of evolutionary development. But the theory cannot sustain a very detailed analysis, as might be expected in the light of our modern knowledge of genetics and development. So long as a given set of genes survives in any kind of organism, these ancient genes will continue to preserve the ancient characteristics of the stock, although newer genes may modify and obscure these old effects at any stage of development. Moreover, some genes in every stock seem to be so crucial in embryonic development, that few, if any, mutations in these genes are tolerable

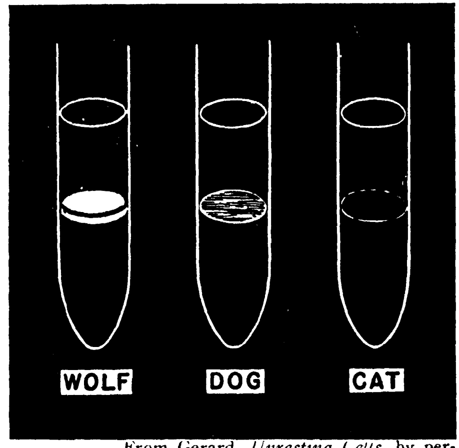
to the organism. Consequently such genes are preserved in the course of natural selection, and are responsible for the recapitulation of certain age-old characteristics in every species.

Biochemical Relationships Among Organisms. Genetic relationships between different organisms are clearly indicated not only by their structural and developmental characteristics, but also by their chemical composition—particularly with reference to their protein components. The proteins extracted from corresponding tissues of closely related animals tend to be very similar, or sometimes identical; whereas more distantly related species show much greater differences in this respect. Take, for example, the blood proteins of vertebrate animals, which have been studied very extensively in recent years. The antigenic reactions (p. 398) of bloods from the various races of man prove to be quite identical, and almost identical with the antigenic reactions of bloods from the anthropoid apes. The bloods of old world monkeys come next in their relationship to human blood; while the bloods of American monkeys and lemurs (Fig. 336) show a less and less intimate relationship. In this way many degrees of relationship between the bloods of all Mammals can be demonstrated (Fig. 337); and similarly all birds are found to have a fairly close relationship to each other, and more distant ties to members of the reptile group (Fig. 338). All in all, more than a thousand animals, in several different phyla, have been classified in accordance with their blood and tissue reactions, and generally speaking, these tests indicate the same relationships as were derived from structural and developmental studies. Thus these biochemical relations—which were discovered long after the theory of evolution had gained general acceptance—strikingly confirm the conclusions which were based originally upon totally different grounds. Apparently the biochemical similarities between related species come from the same sources as their structural and developmental similarities—the possession of a common fund of genes derived from a common ancestry.

Paleontology: The Fossil Record. A *fossil* is any sort of remnant, or trace, left by an ancient pre-existing form of life

Fig. 336.—Probable interrelations of the primates, and the fossil forms most closely in the line of human ancestry: 1, Notharctus, a primitive lemuroid primate; 2, Propliopithecus, a primitive ape; 3, Dryopithecus, a somewhat man-like ape; 4, Pithecanthropus, the "ape-man"; 5, Eoanthropus, the "dawn man"; 6, Homo heidelbergensis; 7, Homo neanderthalensis; 8, oldest fossil remains of Homo sapiens.

(Figs. 339 and 340); and the study of fossils constitutes the science of *paleontology*. A few fossils are found in sand-drifts, asphalt, amber (petrified resin), and in the ice of arctic regions; but a vast majority of fossils are found in *sedimentary* rocks. These stratified rocks are formed *under water*, by the slow deposition of sand, clay, mud or lime, which subsequently



From Gerard, *Unresting Cells*, by permission of Harper and Brothers

FIG. 337.—The serum of a rabbit "immunized" with wolf blood will cause a heavy precipitate of the proteins of wolf plasma when this plasma is added to the rabbit serum in a test tube. The chemically similar proteins of dog blood give a faint precipitate, but the quite different ones of cat's blood react scarcely at all.

harden into rock, under the action of high pressure and a series of slow chemical transformations.

The fossil record, as it is known today, provides only a very fragmentary history of the life of past ages; but this fact is not surprising in view of the peculiar chain of chance and circumstance necessary for the formation, preservation and discovery of fossils. Usually only the hard parts of any creature—such as shell, or bone, or wood—are likely to survive as fossils; and since a majority of very early organisms never possessed any skeletal parts, vast multitudes of ancient forms have left only the barest traces of their existence. Also the fossils found in sedimentary rock, by the nature of their origin, are derived mainly

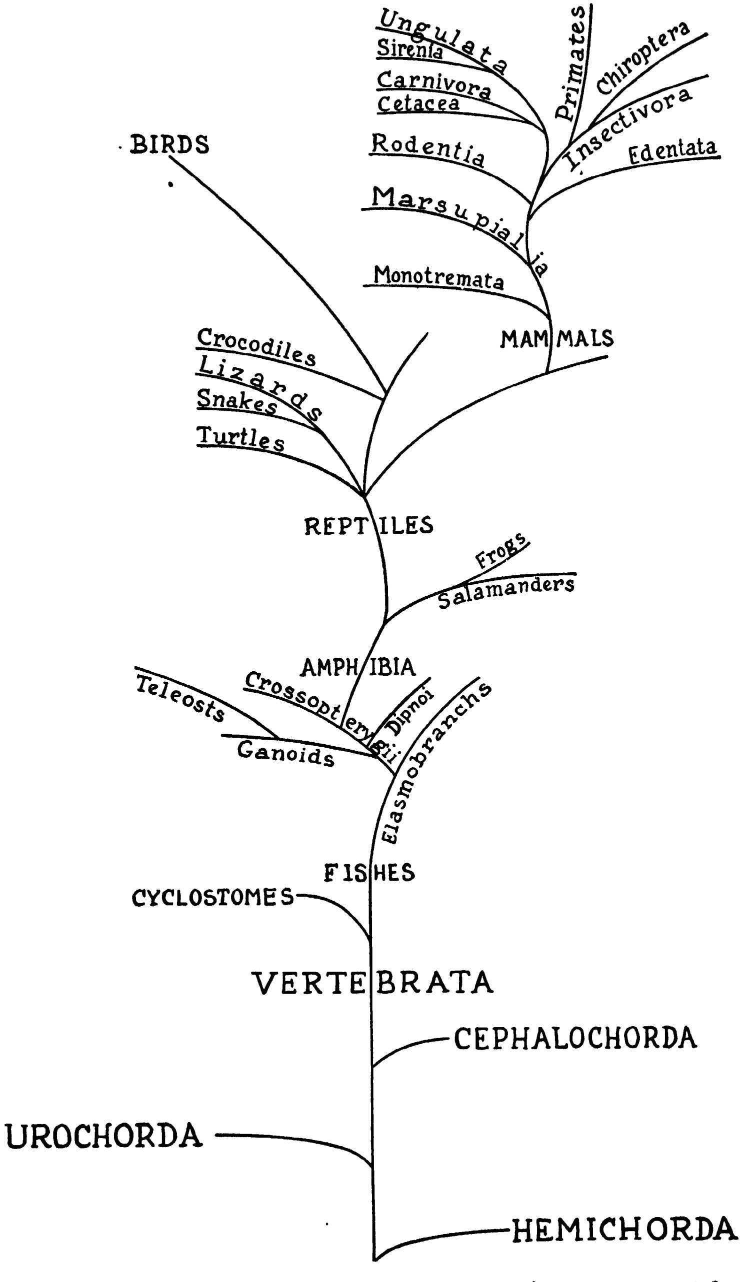


FIG. 338.—Probable interrelations of the chordates (the groups are defined in Appendix I).

from aquatic organisms or, more especially, from species which have dwelt in the ocean. Only rarely does it happen that the remains of a land-dwelling form finds its way to the oceanic floor,

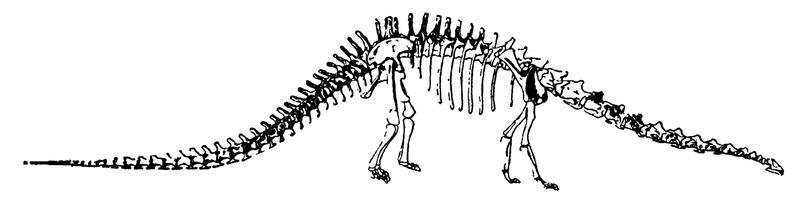


Courtesy of the American Museum of Natural History, New York

FIG. 339.—Foot of a dinosaur, Diplodocus, as uncovered in the Bone Cabin Quarry, Wyoming.

and consequently terrestrial species, on the whole, are rather poorly represented in the fossil record. Moreover, sedimentary rocks are deposited only under certain conditions—relatively near the shore, where large amounts of sediment are accumlating, in areas which are *sinking*, so that the accumulation may reach considerable depth. And once formed, fossils are susceptible to destruction. Very deeply buried sedimentary rocks begin

to suffer distortion or *metamorphosis*, as a result of great pressure or heat, and these factors may destroy or obliterate a large part of the fossil content. If, on the other hand, such rock is *raised* and exposed to the *eroding* action of running water, wind, rain, sleet, frost, etc., again there may be a wholesale destruction of the fossil record. And finally, fossils which escape the vicissitudes of the ages can be discovered during this present age, only if they happen to lie at or near the surface of the earth, in some accessible region (Fig. 341). Considering all these fac-



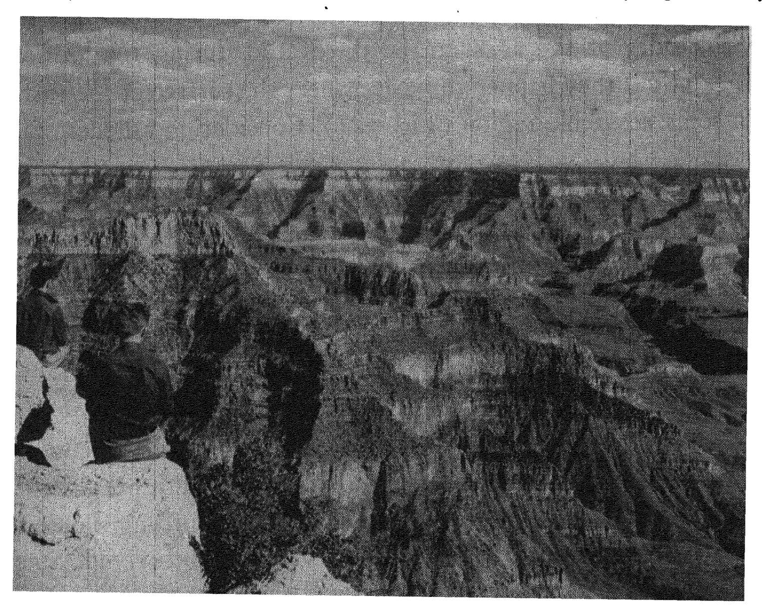
Courtesy of the American Museum of Natural History, New York

FIG. 340.—Total skeleton of a dinosaur, Diplodocus.

tors, therefore, it is not surprising that the record of pre-existing species is far from complete. In fact, the surprising thing to find is that so much has been preserved and discovered. Since the time of Darwin—who emphasized the meagerness of fossil data—paleontologists have advanced great lengths toward the completion of the record (Fig. 342), especially with reference to species which became extinct during the more recent periods of geological time.

Geological Strata and Their Relative Ages. The layers, or *strata*, of sedimentary rock, because of the nature of their origin, occur in the sequence of their deposition, such that all newer (later) strata are superimposed upon the older (earlier) layers. Consequently the deeper is the stratum, the older is its content of fossils. However, the problem of determining the *relative ages* of the various geological strata is not always so very simple, because not all the strata are to be found in any one locality. Some land areas were exposed at times when others

were submerged, so that great gaps are present in the strata of any given region. Also some areas experienced re-submergence after many centuries of exposure—during which erosion carried away many of the upper strata. Therefore, in some cases, relatively recent strata are found superimposed directly upon very



Union Pacific Railroad Photo

FIG. 341.—Layer after layer of stratified rock, exposed in the Grand Canyon of the Colorado River. Here the canyon is a mile deep.

ancient layers. But despite the gaps, the older strata in any one locality are always found to be deeper than the newer layers, except in rare cases where there has been a demonstrable folding of the crust of the earth and an inversion of the strata. And once the relative age of a certain stratum has been determined on other grounds, the fossils of this stratum provide an invaluable clue for the identification of the corresponding stratum in other regions of the earth.

Eras and Periods of Geological Time. The earlier geologists were able to identify five well-defined *series* of strata, but found considerable gaps between the series, and smaller gaps

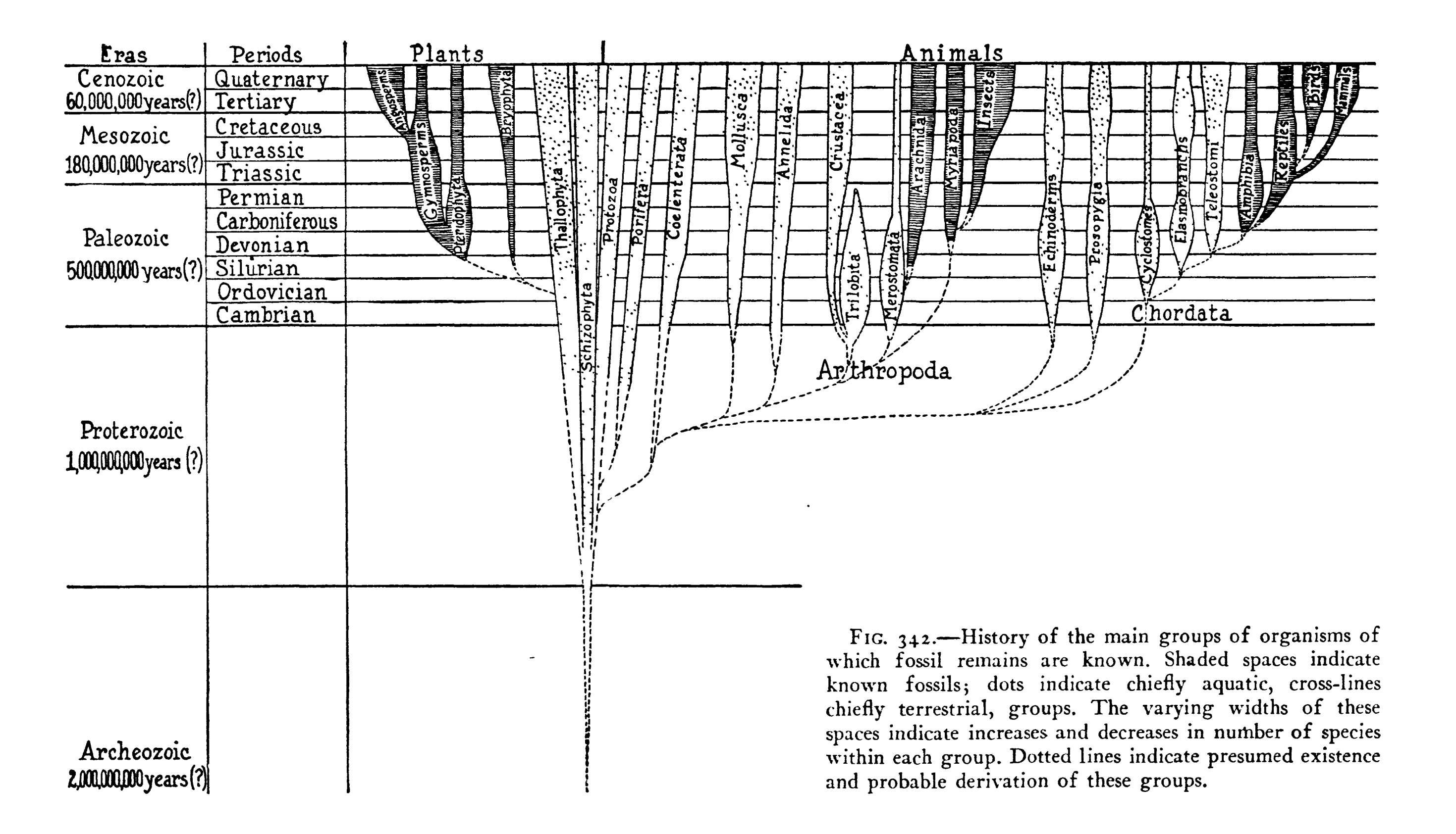


FIG. 342.—History of the main groups of organisms of which fossil remains are known. Shaded spaces indicate known fossils; dots indicate chiefly aquatic, cross-lines chiefly terrestrial, groups. The varying widths of these spaces indicate increases and decreases in number of species within each group. Dotted lines indicate presumed existence and probable derivation of these groups.

within each series. On the basis of these gaps, the strata were divided and subdivided into the eras and periods of geological time, as is shown in Table XXIII. Subsequently the study of the strata has progressed considerably, extending to ever wider regions of the earth. Thus many of the gaps have been filled in, and the lines of demarcation between the eras and periods are becoming less sharply and arbitrarily defined.

The *relative* duration of the eras and periods of geological time is quite plainly indicated by the thickness of their strata, although considerable variation must have occurred in the rate at which sedimentary rock was deposited in different areas and at different times. In fact, until recently there was little hope of obtaining reliable estimations as to the *absolute* duration of the geological periods. Now, however, physicists have found that the proportion of radioactive elements contained in certain rock provides an excellent index of the absolute age. Uranium, for example, gradually transforms into lead by a series of radioactive disintegrations; and the rate of this disintegration is independent of temperature and the other variables of the environment. Specifically, it requires 3.7 billion years for half of a given sample of uranium to degrade into lead. Therefore, in rocks which are devoid of lead except for that which has been derived from uranium, the lead : uranium ratio gives an accurate measure of the absolute age. These age measurements are in excellent agreement with the most recent and reliable data based on sedimentation rates. Consequently the durations of the eras, as specified in Table XXIII, can be accepted with a fair degree of confidence.

Brief Survey of the Fossil Record. The main outlines of the history of pre-existing life are shown in Fig. 342 and Table XXIII; and the ensuing account will attempt little more than to exemplify a few of the major evolutionary trends.

No recognizable fossils are found in the Archeozoic strata, but all these rocks are badly metamorphosed and eroded. However, the presence of graphite and other materials of presumably organic origin, indicate that the very earliest forms of life had their beginnings in the Archeozic period.

Table XXIII

ORIGIN OF ORGANISMS IN RELATION TO THE EARTH'S HISTORY

Eras	*Periods*	*Main Characteristics of the Environment*	*Existing Forms of Life*
Cenozoic ±60 million years	Quaternary.... Tertiary	Land areas like today's; periodic glaciation Elevation of mountains, including Alps and Himalayas; climate growing colder	Continuance of all pre-existing phyla; origin and rapid spread of man; rise of the grasses; replacement of archaic mammals by the modern placentate forms
Mesozoic ±180 million years	Cretaceous .. Jurassic. . Triassic.	Extensive swamplands, followed by elevation of the Rocky and Andes mountain ranges Small continents; much lowland near the sea Great desert areas	Continuance of all pre-existing phyla; origin of the birds and Mammals; rise and fall of gigantic reptiles (dinosaurs), flying reptiles (pterodactyls) and toothed birds; spread of the cycads and conifers; extinction of forests of large ferns, horse-tails and club-mosses
Paleozoic ±500 million years	Permian Carboniferous Devonian . Silurian . . . Ordovician. . . Cambrian.....	Mountain building Large continents, rising mountains; warm humid climate Smaller inland seas; land emergence Great inland seas; warm climate Land submergence; warm even in the Arctic Extensive lowlands	No birds or Mammals, and only a few primitive Angiosperms; primitive Bryophytes, Pteridophytes and Gymnosperm , starting in the Devonian strata; origin of the Molluscs, Annelids, Arthropods, Echinoderms, and Chordates as early as the Cambrian period; land vertebrates start in the Carboniferous; great dominance of Trilobites (primitive Arthropods) in early periods, but extinction in the later
Proterozoic ±1,000 million years		Little known; some evidence of extensive repeated glaciation	Mainly unicellular plants (Schizophytes) and animals (Protozoa); and, towa d, the end, a few simple Thallophytes and sponges (Porifera). No higher invertebrates, nor any vertebrates
Archeozoic ±2,000 million years		Conditions altogether problematical	No recognizable fossils; indirect evidence indicates some primitive organisms toward the end of the Archeozoic era

In Proterozoic rocks, fossils are still relatively scarce and poorly preserved, but quite a few are plainly recognizable. The very earliest fossils are identified as primitive Schizophytes;

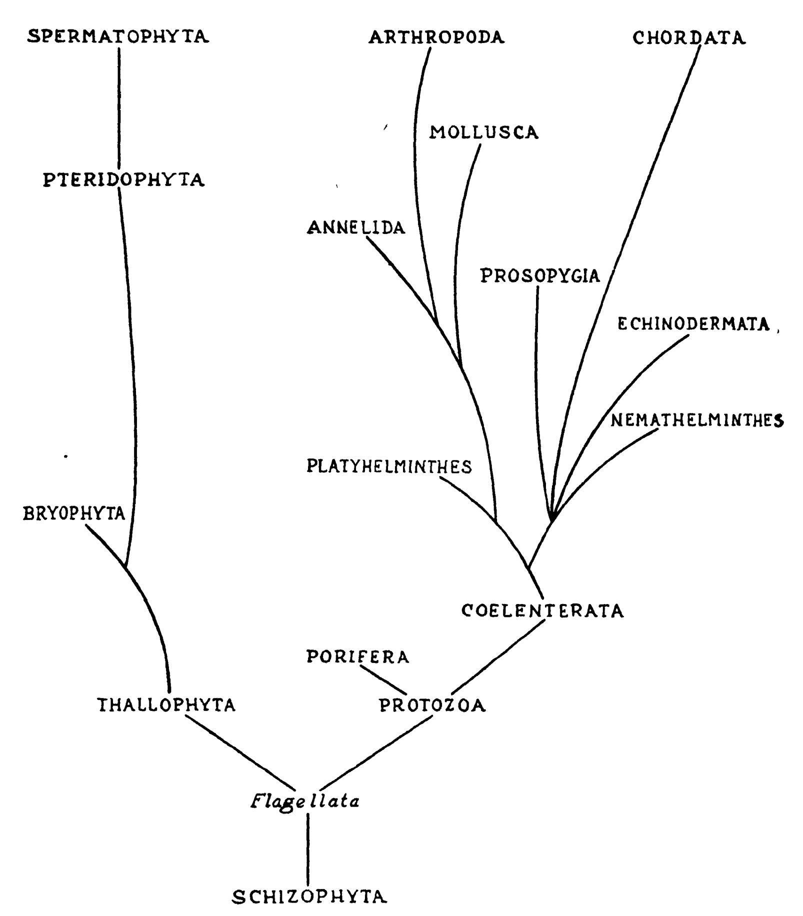


FIG. 343.—Probable relations of the main phyla of plants and animals.

and most biologists agree that the earliest organisms were colorless plants similar to our modern autotrophic bacteria (p. 196). In the upper Proterozoic strata there are unmistakable fossil remains of algae (akin to the modern Thallophytes), numerous Protozoa, a few sponges (Porifera), and—near the very top—a few other invertebrate groups (Fig. 343).

A considerable gap exists between the strata of the early Paleozoic and the late Proterozoic eras; i.e., no sedimentary rocks formed during this interval have been found on the land surfaces as they exist today. In fact the geological evidence indicates that most of the land areas of today were also land areas toward the end of the Proterozoic period. The earliest Paleozoic (*Cambrian*) strata contain a rich fossiliferous record; with an abund-



Courtesy of The Yale Peabody Museum

FIG. 344.—Fossil of a Paleozoic insect (Dunbaria fasciipenis).

ance of algae and some representatives of all the principal invertebrate phyla. However, the Cambrian strata show no Vertebrates, no plants higher than Thallophytes, and, in fact, no *terrestrial organisms of any kind.* All life at this time was still aquatic. Moreover, Cambrian animals, while belonging to the same phyla as our modern species, were generally quite different. On the whole they were more primitive than the present species, and in many cases like the Trilobites (Fig. 342), they belonged to groups which are now extinct.

Quite early in the Paleozoic era (Ordovician strata), the *first fossil Vertebrates* are represented, as primitive fish-like forms. Shortly thereafter (Silurian strata) the *first land plants* appear, followed (in the Silurian and Devonian periods), by primitive *Amphibia* and *Reptiles,* which also began to invade the land. The later strata of the Paleozoic era continue to show

a rich though varying representation of most of the earlier groups, but in addition they reveal the flourishing of many *land-dwelling* species: Bryophytes, Pteridophytes and Gymnosperms, among the plants; Reptiles and Amphibia, among the Vertebrates; and Insects (Fig. 344) and other Arthropods among the Invertebrates. Extensive swampland forests (Fig.

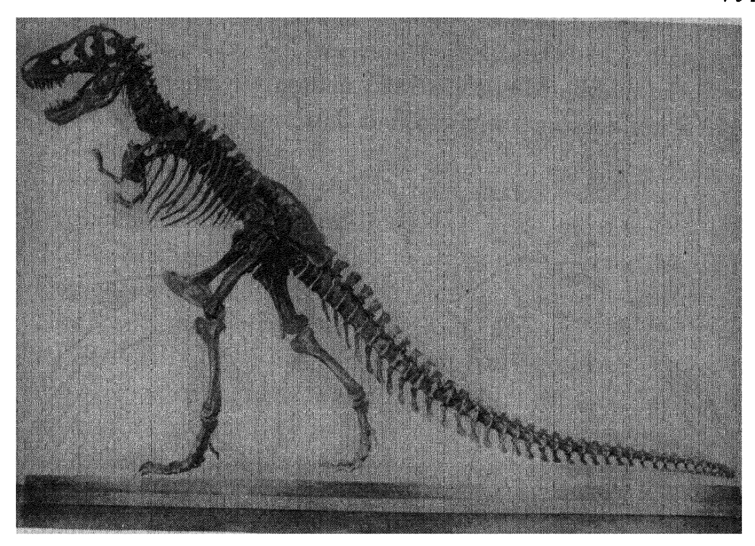


Courtesy of the Chicago Natural History Museum

Fig. 345.—Restoration of a carboniferous swamp forest. Note the giant ferns, horsetails and club-mosses; the primitive conifers; and the large primitive insect.

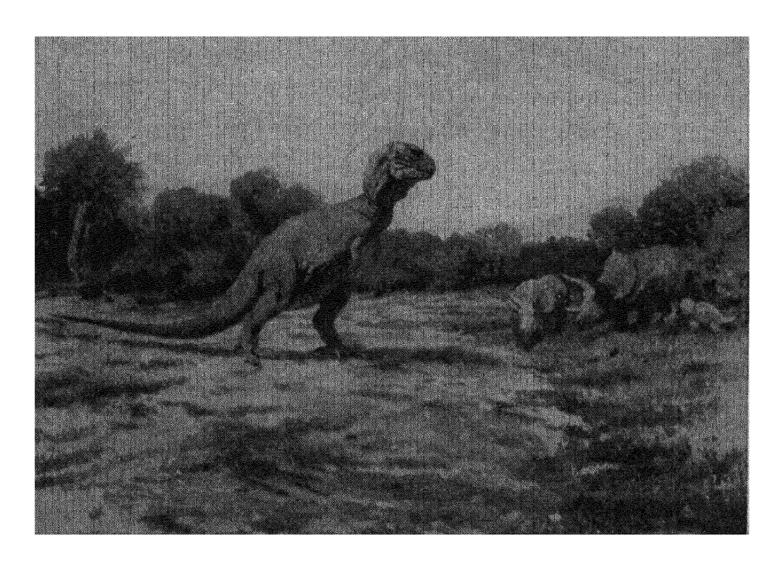
345), composed of gigantic ferns and other Pteridophytes, together with a few primitive Gymnosperms, flourished in the latter parts of the Paleozoic period; and fish became the dominant animals of the sea. However, none of the flowering plants (Angiosperms), nor any of the Birds and Mammals appear to have arisen before the close of the Paleozoic era.

The early Mesozoic strata show a great diversification of the reptile group, not only as to forms resembling the modern lizards, turtles, snakes and so forth, but also as to archaic forms like the gigantic *Dinosaurs* (Figs. 346 and 347), and the flying reptiles (*Pterosaurs*). Also in the early Mesozoic rocks one



Courtesy of the American Museum of Natural History, New York

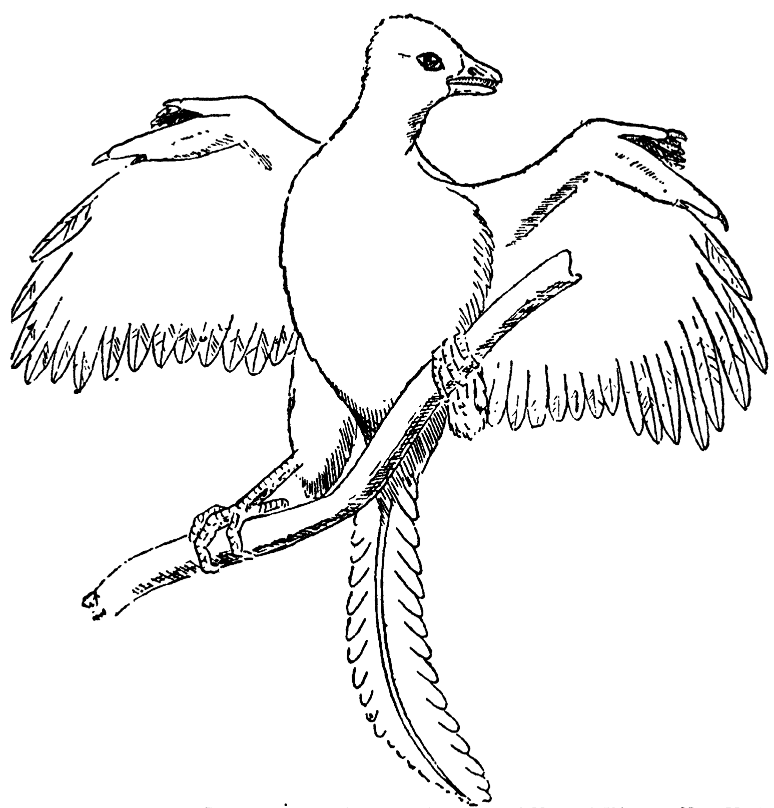
FIG. 346.—Whole skeleton of another dinosaur, Tyrannosaurus rex, from the Cretaceous strata of Hell Creek Basin, Montana.



Courtesy of the American Museum of Natural History, New York

FIG. 347.—Tyranosaurus and Triceratops, a restoration by Charles R. Knight.

finds the first *primitive Mammals.* But the *first Birds,* such as the toothed and clawed *Archeopteryx* (Fig. 348), are not found until the middle Mesozoic strata; and only in the upper Mesozoic strata does one begin to find flowering plants and *modern*



Courtesy of the American Museum of Natural History, New York

FIG. 348.—A primitive Jurassic bird, Archaeopteryx. Note the teeth, the elongate tail, and the clawed wings.

insects. The close of the Mesozoic era also marks the extinction of most of the numerous ancient reptilian hordes that had dominated the land and air for a hundred million years. Hardly a single fossil trace of the many kinds of Dinosaurs, Pterosaurs and other primitive types of reptiles, are to be found in any of the Cenozoic strata.

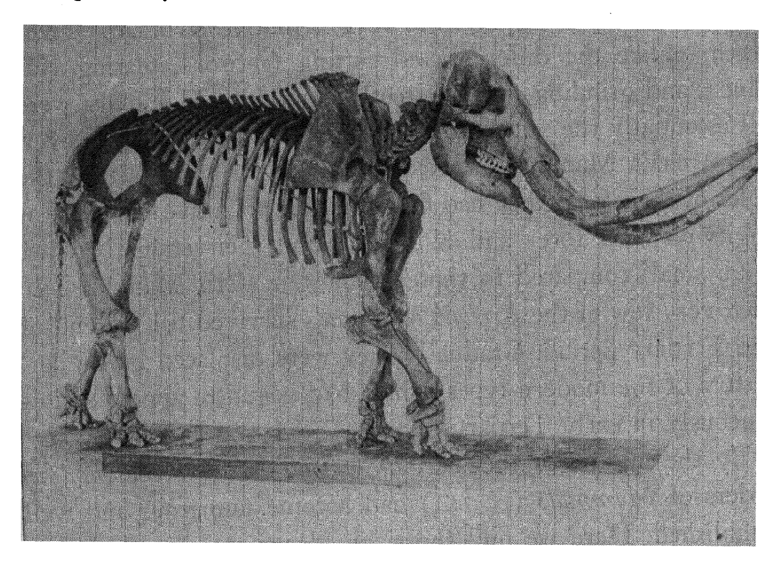
The Cenozoic era, in which we live, is characterized by a very abundant fossil record; but to consider the details of this record would carry us far into the field of Paleontology. Very briefly it can be said, however, that the Cenozoic era is the *age of Mammals* and *Angiosperms*.

By the beginning of the Tertiary period quite a variety of *Archaic Mammals* had usurped the place of the Dinosaurs. These Mammals displayed a very primitive structure. Their teeth, unlike the differentiated cutting (incisor), tearing (canine), and grinding (molar) teeth of modern Mammals, were all essentially the same—like typical reptilian teeth. Moreover, the Archaic Mammals walked, not on their toes, but on the soles of their feet; they had five (the full primitive number) of digits on both fore- and hind-feet; and their cranial cavities were small compared to those of most modern Mammals. In fact, very few of the *Archaic Mammals* survived till the end of the Tertiary period. Gradually they were displaced by the ancestors of the modern types, which had begun to appear simultaneously in early Tertiary times.

By the middle of the Tertiary period most of the *modern* orders of *Mammals* (p. 744) had become numerous and well established. Here we find the richly documented evolutionary stages of the Ungulates (horses, camels, elephants, cattle, swine, etc.); the Carnivores (tigers, lions, cats, dogs, etc.); Rodents (squirrels, rabbits, rats, mice, etc.); Primates (monkeys, apes, lemurs, etc.); and so forth. In fact, the peak of the ascendancy of the Mammals (excluding man) was reached before the close of the Tertiary period. In the latter part of this period, there were great herds of Mastodons (Fig. 349); but these elephantine creatures became extinct before the onset of the recent epoch.

The Tertiary period also records the rise of the Angiosperms to ascendancy in the plant kingdom. Particularly important was the spread of the grasses, which provided food for the herbivorous Mammals; and the extension of the deciduous forests, which afforded protection for a wide variety of mammalian types.

The first manlike fossils began to appear quite late in the Tertiary (Fig. 336); but undeniable evidence of the genus Homo is not found until early in the Quaternary period. The fossil record of the descent of man is not so complete as that of many other Mammals (e.g., the horse, camel, elephant, etc.), due probably to the fact that the forest habitat and mode of



Courtesy of the American Museum of Natural History, New York

FIG. 349.—Mastodons were very numerous toward the end of the tertiary period.

life among the early primates were not conducive to fossilization. However, the evidence is clear enough to show that man owes his origin to apelike creatures (Fig. 350), which in turn were derived from lower primates. In fact, when one traces the fossil record, it is impossible to draw a sharp line between the apes and the several species of "man" which existed in the Pleistocene epoch. Also it is clear that all races of man which are alive today belong to a single species, *Homo sapiens;* and that the oldest fossil remains of this species are found in the late Pleistocene strata, which were formed about 150,000 years ago.



Courtesy of the American Museum of Natural History, New York

FIG. 350.—Skull and facial restorations of various prehistoric men, by J. H. McGregor. From left to right: 1, the Java man, Pithecanthropus; 2, the Piltdown man; 3, the Neanderthal man; and 4, the Cro-Magnon man. In 1 and 2, the lighter parts are restorations, deduced from the anatomy of the other parts.

TEST QUESTIONS

1. Explain how a study of the classification of a given group of organisms (e.g., vertebrates) leads to the conclusion that all the types belonging to the group (e.g., fish, amphibia, reptiles, birds, and mammals) are variously interrelated by descent.
2. List twenty features possessed by all vertebrate animals but not by any other group of animals.
3. Explain how and why a biologist can predict many things about an animal or plant he has never seen, provided he is merely told the phylum and the class of the unknown organism.
4. Specify:
   a. five human bones which have homologous parts in the frog's skeleton;
   b. four parts of man's digestive tract for which there are homologous organs in the frog;
   c. four parts of man's excretory system for which there are homologous organs in the rat;
   d. five parts of man's nervous system for which there are homologous parts in all other vertebrates.
5. What is the justification for considering that the arm of a man is homologous to:
   a. the wing of a bird?
   b. the fore-limb of a frog?
6. Explain the basis for the statement that a reptile, essentially, is "a patched-up and made-over amphibian"?
7. What is a vestigial structure? Mention three of man's vestigial structures. How are vestigial structures to be accounted for?
8. How does a human embryo resemble the embryos of fish (and other vertebrates) in regard to:
   a. origin, position and structure of the nervous system;
   b. stages in the development of the skeletal system;
   c. origin and development of the circulatory organs?
9. To what extent does a human embryo in the "gill-slit stage" tend to resemble a fully developed fish?
10. Explain and discuss the theory of recapitulation, pointing out its strengths and weaknesses.
11. Explain the genetic basis of the recapitulation tendency.

12. Explain how a study of the comparative biochemistry of the tissues (e.g., blood) of various groups of animals and plants can be used to reveal genetic relationships amongst the groups.
13. Carefully define: (a) paleontology; (b) a fossil; (c) sedimentary rock; (d) erosion; (e) metamorphosis (of rock); (f) a geological stratum.
14. Explain how it is possible to estimate:
    a. the relative age of a given geological stratum;
    b. the absolute age of certain strata.
15. Distinguish between the eras and periods of geological time.
16. Briefly discuss each of the following topics:
    a. origin of the Schizophytes and Protozoa;
    b. origin of the Thallophytes and Porifera;
    c. origin of the higher invertebrate phyla, and of the earliest vertebrates;
    d. first appearance of land plants (Bryophytes, Pteridophytes and Spermatophytes); origin of land vertebrates;
    e. origin and extinction of the forests of giant ferns and other Pteridophytes;
    f. the rise and fall of the dinosaurs and other primitive reptilian forms; origin of the birds and Mammals; the heyday of the cycad and conifer forests;
    g. the replacement of the archaic Mammals by the modern mammalian forms;
    h. the rise of man.
17. List at least ten different fields of study that contribute significant evidence as to the mechanism and course of evolution.

FURTHER READINGS

1. *Man and the Vertebrates*, by A. S. Romer; Chicago, 1933.
2. *Men of the Old Stone Age*, by H. F. Osborn; New York, 1918.
3. *Organic Evolution*, by R. S. Lull; New York, 1929.
4. *Embryos and Ancestors*, by G. R. DeBeer; Oxford, 1940.

APPENDIX I

CLASSIFICATION OF ORGANISMS

The classification of organisms down to classes (in some cases to subclasses) is given in the following pages. The phyla, within each kingdom, and the classes within each phylum are arranged, so far as possible, in order of increasing complexity.

The number of species given for each phylum is the approximate number of living species described and named. In many, probably most, phyla there are undoubtedly many more species still undescribed.

Kingdom **PLANTAE**:

Organisms usually having rigid cell walls; nutrition autotrophic, saprophytic, or parasitic. The line between the plant and animal kingdoms is not at all sharp, as explained in the text.

Phylum **SCHIZOPHYTA**: unicellular or simple colonial organisms, with no sharp distinction between nucleus and cytoplasm and no sexual reproduction. (3,000 species.)

Class **Bacteria** (or **Schizomycetes**): the bacteria (pp. 19, 29, 193, 196; Figs. 9, 11, 72, 73, 74).

Class **Cyanophyceae** (or **Schizophyceae**): the blue-green algae (p. 19; Fig. 9).

Phylum **THALLOPHYTA**: unicellular, colonial, or simple multicellular plants, with distinct nucleus and cytoplasm and usually some form of sexual reproduction; without true leaves, stems, or roots; usually without regular alternation of generations; ordinary cells usually haploid. (80,000 species.)

Class **Flagellata**: the flagellates (Fig. 63); these organisms, connecting the plant and animal kingdoms (Fig. 343), may be classified equally well as either Thallophyta or Protozoa. Example: *Euglena* (Fig. 70).

Class **Chlorophyceae**: the green algae; a rather heterogenous group, often divided into several classes. Examples: *Protococcus*

(Fig. 65), *Chlamydomonas* (Fig. 63), *Volvox*, etc. (Fig. 42), *Closterium* (Fig. 63), *Spirogyra* (Fig. 58), *Vaucheria* (Fig. 10), *Ulothrix* (Figs. 36, 126), *Nitella* (Fig. 127).

Class **Phycomycetes**: simple fungi (molds) with syncytial mycelia. Example: *Mucor* (Fig. 69).

Class **Phaeophyceae**: the brown algae.

Class **Rhodophyceae**: the red algae.

Class **Eumycetes**: fungi with multicellular mycelia (except in the unicellular yeasts); often divided into two classes, Ascomycetes and Basidiomycetes. Examples: yeasts (Fig. 68), *Aspergillus* (Fig. 69), mushrooms, puffballs, etc.

Phylum **BRYOPHYTA**: multicellular, usually terrestrial, plants, with regular alternation of generations; the sporophyte always dependent on the gametophyte. (17,000 species.)

Class **Hepaticae**: the liverworts; usually simple, flat plants without stem or leaves. Example: *Marchantia* (Fig. 129).

Class **Musci**: the mosses (Fig. 97).

Phylum **PTERIDOPHYTA**: vascular plants with regular alternation of generations; both generations usually independent, but the sporophyte much the larger and longer-lived. (5,000 species.)

Class **Filicineae**: the ferns (Figs. 87, 88).

Class **Equisetineae**: the horsetails or scouring-rushes.

Class **Lycopodineae**: the club-mosses. Example: *Selaginella* (Fig. 99).

Phylum **SPERMATOPHYTA**: the seed-plants, vascular plants reproducing by seeds; gametophyte very small and dependent on the sporophyte. (130,000 species.)

Subphylum **GYMNOSPERMAE**: conifers, cycads, etc.; no ovule case or true flowers (Fig. 345).

Subphylum **ANGIOSPERMAE**: flowering plants; ovules completely enclosed in an ovule case. (Figs. 102-104.)

Class **Monocotyledoneae**: grasses, lilies, orchids, etc.; embryo with a single cotyledon; vascular bundles scattered through the stem; leaves with parallel veins; flower parts in threes or sixes (Fig. 109).

Class **Dicotyledoneae**: most flowering plants; embryo with two cotyledons; vascular bundles in a ring in the stem; leaves with netlike venation; flower parts in fours or fives (Fig. 113).

Kingdom **ANIMALIA:**

Organisms usually without rigid cell walls or chlorophyl; nutrition usually holozoic.

Phylum **PROTOZOA:** unicellular or simple colonial animals, usually with distinct nucleus and cytoplasm; with or without sexual reproduction. (8,000 species.)

Class **Flagellata** (or **Mastigophora**): the flagellates (Fig. 70).

Class **Rhizopoda** (or **Sarcodina**): protozoa with pseudopodia. Examples: *Amoeba* (Fig. 59), slime molds (Fig. 10). (The slime molds are sometimes classified as plants, because their spores have cellulose cell walls.)

Class **Sporozoa:** parasitic protozoa, usually without locomotive or ingestive organs.

Class **Infusoria:** protozoa with cilia. Examples: *Paramecium* (Fig. 62), *Vorticella* (Fig. 82).

All the following phyla, consisting of multicellular animals, are called collectively Metazoa; the groups Protozoa and Metazoa are sometimes called subkingdoms.

Phylum **PORIFERA:** the sponges (Figs. 172-174), simple multicellular animals with little "individuality," forming branching, non-motile colonies. (2,000 species.)

Phylum **COELENTERATA:** radially symmetrical, diploblastic ("two-layered") animals. (4,000 species.)

Class **Hydrozoa:** hydra-like animals, often colonial, and often having a regular alternation of asexual and sexual generations. Example: *Hydra* (Fig. 34).

Class **Scyphozoa:** jellyfishes.

Class **Anthozoa** (or **Actinozoa**): sea-anemones and corals.

Class **Ctenophora:** jellyfish-like animals, somewhat more complex in structure than the typical coelenterates, and often classified as a separate phylum.

Phylum **PLATYHELMINTHES:** the flatworms, bilaterally symmetrical, triploblastic ("three-layered") animals, without a true body cavity or an anus. (5,000 species.)

Class **Turbellaria:** non-parasitic flatworms. Example: *Planaria* (Figs. 177, 178).

Class **Trematoda:** the flukes, parasitic flatworms with an enteron.

Class **Cestoda:** the tapeworms, parasitic flatworms with no enteron, absorbing nourishment through the body surface.

The two following classes are somewhat more complex in structure than the typical flatworms, and are often classified as separate phyla. Their closest relationships are probably to the flatworms, and they may be included in this phylum as a matter of convenience.

Class **Nemertinea**: worms resembling flatworms, but with an anus and blood-vessels.

Class **Rotifera**: microscopic, usually free-swimming, animals, with an anus and body-cavity.

Phylum **NEMATHELMINTHES**: the roundworms, elongate cylindrical worms with an anus and body-cavity. The relationship of the three classes included here is doubtful; they are placed together in this phylum as a matter of convenience. (1,500 species.)

Class **Nematoda**: the typical roundworms, including both free-living and parasitic forms.

Class **Acanthocephala**: parasitic worms with no enteron, absorbing nourishment through the body surface.

Class **Chaetognatha**: free-swimming marine worms, of somewhat more complex structure than the typical roundworms; coelom developed from enteric pouches, as in the two following phyla and the lower chordates.

Phylum **PROSOPYGIA** (or **MOLLUSCOIDA**): animals with a true coelom, developed from enteric pouches; the enteron U-shaped, so that the anus is near the mouth. (2,000 species.)

Class **Bryozoa** (or **Polyzoa**): minute animals forming branching colonies, superficially resembling colonial hydroids.

Class **Phoronida**: worm-like animals living in membranous tubes in the sand.

Class **Brachiopoda**: animals forming shells resembling those of bivalve molluscs.

Phylum **ECHINODERMATA**: radially symmetrical animals, with well-developed coelom formed from enteric pouches.

(3,000 species.)

Class **Crinoidea**: feather-stars, sessile animals often having a jointed stalk for attachment.

Class **Asteroidea**: starfishes.

Class **Ophiuroidea**: brittle-stars.

Class **Echinoidea**: sea-urchins.

Class **Holothuroidea**: sea-cucumbers.

Phylum **ANNELIDA** (or **ANNULATA**): segmented worms, usually with well-developed coelom and blood vessels. (4,000 species.)

Class **Archiannelida**: marine worms, simpler than other annelids.

Class **Chaetopoda**: marine, fresh-water, and terrestrial segmented worms. Example: earthworm (Figs. 180, 237).

Class **Hirudinea**: leeches.

Class **Gephyrea**: marine worms of doubtful relationships, unsegmented in the adult stage.

Phylum **MOLLUSCA**: unsegmented animals, usually with a shell. (60,000 species.)

Class **Amphineura**: the simplest types of molluscs; *Chiton*, etc.

Class **Pelecypoda**: bivalve molluscs; clams, oysters, mussels, scallops, etc.

Class **Scaphopoda**: molluscs with a conical tubular shell; *Dentalium*, etc.

Class **Gastropoda**: asymmetrical molluscs, usually with a spiral shell; snails, etc.

Class **Cephalopoda**: octopus, squid, cuttlefish, nautilus, etc.

Phylum **ARTHROPODA**: segmented animals with jointed appendages. (400,000 species.)

Class **Crustacea**: lobsters, crabs, crayfishes, shrimps, etc.

Class **Arachnida**: spiders, mites, scorpions, etc.

Class **Onychophora**: simple, worm-like, terrestrial arthropods; *Peripatus*.

Class **Myriapoda**: centipedes and millipedes.

Class **Insecta**: insects. Example: *Drosophila*.

Phylum **CHORDATA**: animals having at some stage a notochord, gill-slits, and a hollow nerve-cord on the dorsal side. (30,000 species.)

Subphylum **HEMICHORDA** (or **ENTEROPNEUSTA**): worm-like animals with a notochord-like structure in the head end; *Balanoglossus*, etc.

Subphylum **UROCHORDA** (or **TUNICATA**): tunicates; sac-like, usually sessile animals, often forming branching colonies; in the larval stage they have a notochord in the tail region.

Subphylum **CEPHALOCHORDA**: lancelets; somewhat fish-like animals, with a permanent notochord the whole length of the body; no cartilage or bone (Fig. 162).

Subphylum **VERTEBRATA**: the vertebrates; notochord surrounded or replaced by cartilage or bone, forming the vertebral column or backbone.

Class **Cyclostomata**: lampreys and hagfishes, eel-like animals without limbs or jaws.

Class **Pisces**: fishes, aquatic vertebrates breathing by gills; single circulation; skin usually covered with scales; the limbs are fins.

Subclass *Elasmobranchii:* cartilaginous fishes, with no air-bladder or lungs; sharks and skates.

Subclass *Teleostomi:* bony fishes, usually having an air-bladder or lung; including the Crossopterygii, Dipnoi (lungfishes), ganoids, and teleosts; the first three of these groups are almost extinct, the teleosts comprising the great majority of living fishes.

Class **Amphibia**: salamanders, frogs, and toads; usually breathing by gills in the larval stage, by lungs in the adult stage; incomplete double circulation; skin usually naked; the limbs are legs.

Class **Reptilia**: turtles, lizards, snakes, crocodiles; breathing by lungs; incomplete double circulation; skin usually covered with scales; the limbs are legs (absent in snakes).

Class **Aves**: the birds, warm-blooded animals with complete double circulation, skin covered with feathers, the fore-limbs wings.

Class **Mammalia**: the mammals, warm-blooded animals with complete double circulation, skin usually covered with hair, young nourished with milk secreted by the mother; limbs usually legs (fore-limbs sometimes arms, wings, or fins).

Subclass *Prototheria* (or *Monotremata*): the monotremes, oviparous mammals with imperfect temperature regulation; only two living species, the duck-bill and spiny anteater of Australia.

Subclass *Metatheria* (or *Marsupialia*): the marsupials, viviparous mammals without a placenta (or with a poorly developed one), the young carried in an external pouch of the mother for some time after birth; kangaroos, opossums, etc.

Subclass *Eutheria:* mammals with a well-developed placenta, comprising the great majority of living mammals. The principal orders of Eutheria are the following:

Insectivora: shrews, moles, hedgehogs, etc.

Edentata: toothless mammals; anteaters, sloths, armadillos, etc.

Rodentia: the rodents; rabbits, rats, mice, squirrels, etc.

Ungulata: hoofed animals; cattle, deer, camels, swine, horses, elephants, etc. (often divided into several orders).

Sirenia: the manatee and dugong, aquatic mammals with the fore-limbs fin-like, the hind limbs absent.

Carnivora: carnivorous animals; cats, dogs, bears, weasels, seals, etc.

Cetacea: the whales, dolphins, and porpoises, aquatic mammals with the fore-limbs fins, the hind limbs absent.

Chiroptera: the bats, aerial mammals with the fore-limbs wings.

Primates: the lemurs, monkeys, apes, and man.

APPENDIX II

GLOSSARY

This list does not include names of taxonomic groups, which are defined in Appendix I, nor most terms which are used only once in the text and defined there. In most cases only the meanings of terms as used in this book are given; when other meanings are mentioned they are enclosed in brackets.

ABERRATION. An irregularity of chromosome behavior, resulting in an unusual chromosome complex.

ABSORPTION. The passage of water and dissolved s.bstances into cells.

ACID. A substance which dissociates, yielding hydrogen (H^+)ions.

ACQUIRED CHARACTERS. Somatic modifications; i.e., variations caused by environmental factors.

ACTION CURRENT. An electric current which flows between a region of excitation and neighboring unexcited regions.

ACTIVATION. The stimulation of an egg-cell to start development.

ADAPTATION. Fitness to live and reproduce. Any characteristic of an organism fitting it to live and reproduce.

ADHESION. Attraction between molecules of different substances.

ADRENAL GLANDS. A pair of ductless glands located near the kidneys.

ADRENALIN. A hormone secreted by the adrenal glands.

ADSORPTION. The accumulation of a dissolved substance at the surface between two phases.

AFFERENT FIBER. A nerve fiber carrying impulses from a receptor to the central nervous system.

ALGAE. Simple plants (thallophytes or schizophytes) containing chlorophyl.

ALLELES. Genes occupying the same locus in homologous chromosomes, and which therefore always (normally) segregate from each other at the reduction division.

ALTERNATION OF GENERATIONS. The alternate succession of sexual and asexual forms, each producing the other.

AMICROSCOPIC. Too small to be seen with either the microscope or the ultramicroscope; i.e., less than about 1 mμ in diameter.

AMINO-ACIDS. Organic acids containing both the carboxyl radical (COOH) and the amino radical (NH_2).

AMITOSIS. Division of the nucleus without the appearance of chromosomes or any mitotic figure.

AMOEBOID MOVEMENT. Movement of a cell by means of pseudopodia.

AMYLOPSIN. An enzyme secreted by the pancreas, which partially hydrolyzes starch.

ANAEROBIC METABOLISM. Metabolism without the consumption of free oxygen.

ANALOGOUS ORGANS. Organs having structural similarities correlated with similarity of function and not due to genetic relationship. (*cf.* HOMOLOGOUS ORGANS.)

ANAPHASES. The period of mitosis during which the daughter chromosomes move toward opposite poles.

ANTHER. The part of a stamen containing the pollen.

ANTHERIDIUM. The organ of bryophytes and pteridophytes in which the sperm-cells are formed.

ANUS. The terminal opening of the enteron.
APHIDS. Plant lice, small sucking insects parasitic on plants.
APICAL CELL. A cell at the apex of the growing point of many thallophytes, bryophytes, and pteridophytes, which by continued growth and cell divisions produces all the tissues of the plant.
APOGAMY. Asexual production of a sporophyte from a gametophyte.
APOSPORY. Production of a gametophyte from a sporophyte without a reduction division.
ARCHEGONIUM. The organ of bryophytes and pteridophytes in which the egg-cell is formed.
ARTERY. A muscular, elastic blood vessel, carrying blood from the heart to the capillaries. (*cf.* VEIN.)
ASEXUAL REPRODUCTION. Any method of reproduction not involving fertilization.
ASSIMILATION. The production of protoplasm from food substances in the living cell.
ASTER. A radiating structure surrounding each end of the spindle during mitosis.
ATOMS. The elementary particles which enter into chemical reactions.
AURICLE. A relatively thin-walled chamber of the heart which receives blood from the veins and pumps it into the ventricle.
AUTONOMIC NERVOUS SYSTEM. A system of motor neurones innervating the involuntary muscles and glands, connected with the central nervous system by axons of intermediate neurones of the central nervous system.
AUTOSOMES. Chromosomes which are not sex-chromosomes.
AUTOTROPHIC. Able to synthesize all substances required for nutrition from inorganic food substances. (*cf.* HETEROTROPHIC.)
AUXOCYTE. A germ-cell in the growth period, during which synapsis and tetrad-formation occur.
AXON. A long, unbranched or sparsely branched, nerve fiber, usually carrying impulses away from the cell-body of its neurone.
BACK-CROSS. A cross between an individual whose genetic constitution is to be tested and one which is homozygous for all recessive genes involved in the experiment.
BACTERIOPHAGE. A filtrable virus parasitic on bacteria.
BASE. A substance which dissociates, yielding hydroxyl (OH^-)ions.
BAST. The phloem.
BILE. The external secretion of the liver, secreted through the bile duct to the small intestine.
BIOLOGY. The scientific study of living things.
BIVALENT. A pair of homologous chromosomes joined in synapsis. (*cf.* UNIVALENT.)
BLASTOCOEL. The cavity within a blastula.
BLASTOPORE. The external opening of the enteron of a gastrula.
BLASTULA. An embryo after cleavage and before gastrulation, typically a single layer of cells forming a hollow sphere.
BLOOD. A fluid tissue consisting of the blood cells, or *corpuscles*, and a liquid intercellular material, the *plasma*.
BRAIN. The enlarged anterior end of the central nervous system.
BROWNIAN MOVEMENT. The continual random movement of small particles dispersed in a fluid medium, due to their bombardment by the molecules of the medium.
BUDDING. The asexual production of a new individual by the splitting off of a relatively small portion of the parent organism.
BUD. (1) A young individual produced by budding, before it is completely detached from the parent. (2) The end of a stem or branch, enclosed by young leaves; this may develop into a leafy stem (*leaf bud*) or into a flower (*flower bud*).
BULB. A subterranean leaf bud or flower bud.
CALORIE. The quantity of heat required to raise the temperature of 1 kilogram of water 1° centigrade; this is the "large Calorie," the unit always employed in connection with nutrition.
CALYX. The outermost whorl of parts in a complete flower.
CAMBIUM. A layer of embryonic tissue between the xylem and the phloem in dicotyledonous plants.
CAPILLARIES. Very small, thin-walled blood vessels, penetrating the intercellular

spaces of all organs, through whose walls osmotic exchanges occur between the blood and the tissue cells.

CARBOHYDRATES. Compounds of carbon, hydrogen, and oxygen in the proportions of about 1C : 2H : 1O; including sugars, starch, glycogen, cellulose, etc.

CARPEL. A macrosporophyl of a flowering plant, one of the innermost whorl of flower parts.

CATALYSIS. The action of a catalyst.

CATALYST. Any substance which modifies the rate of a chemical change without being itself used up in the process.

CELL. A structural unit of protoplasm, consisting usually of nucleus and cytoplasm.

CELL SAP. The fluid in the large vacuoles of plant cells, a watery solution of salts, sugars, etc.

CELL WALL. The rigid external covering of a plant cell.

CELLULOSE. An insoluble complex carbohydrate (polysaccharide), the chief component of most plant cell walls.

CENTRAL NERVOUS SYSTEM. The main part of the nervous system in most animals, containing the cell-bodies of most of the neurones.

CENTROLECITHAL EGG. An egg-cell containing a large amount of yolk concentrated toward the center.

CENTROSOME. The body or region at the center of an aster.

CEPHALIZATION. The concentration of the sensory and nervous systems at the head end of animals.

CEREBELLUM. An expansion of the dorsal side of the brain near its hind end, the co-ordinating center for proprioceptive stimuli and complex muscular movements.

CEREBRUM. An expansion of the dorsal and lateral sides of the brain at its front end, the chief center for conditioned, or learned, responses.

CHEMICAL AFFINITY. The tendency of particular elements to combine with each other.

CHEMICAL REACTION. A change of one or more substances into different substances, by recombination of their constituent atoms into different kinds of molecules.

CHEMOTROPISM. Movement whose direction is determined by the unequal concentrations of some particular substance on the two sides of an organism.

CHLOROPHYL. The green pigment of plant cells which catalyzes photosynthesis.

CHLOROPLAST. A plastid containing chlorophyl.

CHOLESTEROL. A sterol found in many animals.

CHROMATIN. A substance found in all living cells which stains deeply with certain dyes; the characteristic component of the nucleus.

CHROMIDIA. Granules of chromatin scattered through the cell, chiefly in cells which have no distinct nucleus and cytoplasm, such as bacteria.

CHROMOSOMES. Threads or rods of chromatin which appear during mitosis and split longitudinally.

CILIA. Fine protoplasmic processes which beat in unison to move the cell or move particles over its surface.

CLASS. A taxonomic group, next below a phylum.

CLEAVAGE. The successive cell divisions of the zygote (or parthenogenetic egg) which transform it into a multicellular embryo.

CLOACA. The common posterior opening of the enteron, ureters, and gonoducts in most vertebrates except mammals.

COARSE. Of microscopic or macroscopic size; i.e., above about 100 $m\mu$ in diameter.

COELOM. A cavity containing the gonads, occupying most of the space between the outer body wall and the enteron in annelids, vertebrates, etc.

COHESION. Attraction between molecules of the same substance.

COLLOIDAL. Of ultramicroscopic size, i.e., between about 1 $m\mu$ and 100 $m\mu$ in diameter. Dispersions containing molecules or particles of this size.

COLONIAL ORGANISM. An aggregate of cells all alike in structure and function.

COMPONENTS. The substances making up a mixture. (*cf.* CONSTITUENTS.)

COMPOUND. A substance containing only one kind of molecules, each molecule consisting of two or more kinds of atoms.

CONDITIONED REFLEX. An habitual response to a particular stimulus determined by the

previous experience of the individual, i.e., by the frequent association of this stimulus with a stimulus which originally aroused this response.

CONDUCTOR. A structure specialized for the transmission of excitation.

CONJUGATION. The union of two gametes; usually used only in cases where the two gametes are alike.

CONNECTIVE TISSUES. Tissues in which the cells are irregularly distributed through a relatively large amount of intercellular material.

CONSTITUENTS. The elements making up a compound. (*cf.* COMPONENTS.)

COORDINATION. The production of harmonious interaction of the various parts and processes of an organism.

COPULATION. The introduction of sperm-cells into the body of the female by the male animal.

COROLLA. The whorl of parts next inside the calyx of a complete flower.

CORTEX. The portion of a stem or root between the epidermis and the fibro-vascular bundles.

COTYLEDON. Leaf of an embryo plant within the seed.

CRANIAL NERVES. Nerves arising from the brain.

CROSS-FERTILIZATION. Union of gametes from different individuals. (*cf.* SELF-FERTILIZATION.)

CROSSING-OVER. The exchange of corresponding portions of homologous chromosomes during synapsis.

CRYSTALLOIDAL. Of amicroscopic size; i.e., below about 1 $m\mu$ in diameter. Solutions containing molecules of this size.

CYTOPLASM. The protoplasm of a cell exclusive of the nucleus.

DEATH. Irreversible cessation of the activities and breakdown of the structure of protoplasm.

DEHYDRATION SYNTHESIS. The chemical combination of two or more molecules (of the same substance or different substances) with elimination of water.

DENDRITES. Relatively short and much branched processes of a neurone, usually carrying impulses toward the cell-body.

DENITRIFYING BACTERIA. Bacteria which decompose nitrogen compounds and liberate free nitrogen.

DEVELOPMENT. The progressive production of the phenotypic characteristics of an organism.

DIFFERENTIATION. The structural and functional specialization of different parts.

DIFFUSION. The spreading of a dissolved substance through the solvent by virtue of the random movements of its molecules.

DIGESTION. The hydrolysis of colloidal or insoluble food substances into soluble crystalloidal substances.

DIOECIOUS. Having separate sexes; i.e., the two kinds of gametes produced by different individuals. (*cf.* MONOECIOUS.)

DIPLOID. The number of chromosomes in the zygote, which is twice the number in each gamete. (*cf.* HAPLOID.)

DISACCHARIDE. A carbohydrate which can be hydrolyzed into two monosaccharides; i.e., each molecule of the disaccharide yields two monosaccharide molecules (either alike or different).

DISPERSION. A mixture in which one or more substances are distributed (*dispersed*) throughout another substance (the *dispersion medium*).

DOMINANT. A gene whose phenotypic effect largely or entirely obscures that of its allelomorph. (*cf.* RECESSIVE.)

DORSAL. Pertaining to the upper side (the back in man).

DUCT. (1) A long, hollow, woody tube, in the xylem portion of the fibro-vascular bundles [also called a *trachea* or *vessel*]. (2) The tubular outlet of a multicellular gland of external secretion.

ECOLOGICAL. Pertaining to the relations of organisms to their natural environments.

ECTODERM. The outer layer of cells in the gastrula or, less accurately, the tissues derived from this layer.

ECTOPLASM. A differentiated outer layer of the cytoplasm.

EFFECTOR. A structure specialized for the production of some particular kind of response, e.g., movement or secretion.

EFFERENT FIBER. A nerve fiber carrying impulses from the central nervous system to an effector.

EGESTION. The elimination of solid material from a cell or from the enteron.

EGG-CELL. A large, usually non-motile gamete, containing abundant cytoplasm and yolk. (*cf.* SPERM-CELL.)

ELECTROLYTE. A substance whose molecules dissociate into ions.

ELECTRON. A particle of negative electricity, one of the ultimate constituents of all matter.

ELEMENT. A substance containing only one kind of atoms.

EMBRYO. A young organism before emerging from the egg, the seed, or the body of the mother.

EMBRYO-SAC. The female gametophyte of a seed-plant.

EMULSION. A dispersion consisting of small droplets of one liquid in another.

ENDOCRINE ORGAN. A gland of internal secretion, producing a hormone or hormones.

ENDODERM. The inner layer of cells in the gastrula. The tissues derived from this layer.

ENDODERMIS. The differentiated innermost layer of cells of the cortex of stems and roots.

ENDOPLASM. The inner region of the cytoplasm, as contrasted with the ectoplasm.

ENDOSPERM. A mass of cells, containing stored food substances, developing from part of the embryo-sac and filling all the seed outside the embryo.

ENERGY. The capacity to do work; i.e., to produce change.

ENTERON. The digestive cavity of multicellular animals.

ENVIRONMENT. The external surroundings of an organism.

ENZYME. A catalyst produced by a living organism.

EPICOTYL. The growing point of the stem of an embryonic seed-plant, above the point of attachment of the cotyledons. (*cf.* HYPOCOTYL.)

EPIDERMIS. The outermost layer of cells of a plant or animal.

EPITHELIAL TISSUES. Tissues in which the cells form regular layers, with very little intercellular material.

EPITHELIUM. An epithelial tissue, covering an external or internal surface.

EQUATIONAL DIVISION. A division involving a separation of two identical daughter chromosomes—such as occurs in mitosis and in meiosis.

EREPSIN. An enzyme secreted by the intestine, which hydrolyzes peptones to amino-acids.

ESOPHAGUS. The portion of the enteron between the pharynx and the stomach.

EUSTACHIAN TUBE. A passage connecting the tympanic cavity (middle ear) with the pharynx; developed from the most anterior gill-slit of the embryo.

EVOLUTION. Change of the genetic constitution of a population, by the origin of new genotypes, extinction of old ones, or change in the proportions of the various genotypes composing the population.

EXCITATION. The state of a cell immediately after being stimulated, involving an increased rate of destructive metabolism, increased permeability, and an altered electric charge.

EXCRETION. Elimination of waste products of metabolism.

EXTERNAL SECRETION. Secretion to the outside of the body or into the cavity of the enteron. Any substance or mixture thus secreted.

FAMILY. A taxonomic group, between order and genus; names of plant families end in *-aceae,* those of animal families in *-idae.*

FATS. Lipins which can be hydrolyzed to glycerol and fatty acids, each fat molecule yielding one glycerol molecule and three fatty acid molecules (alike or different). [The term *fats* is often used to include all lipins.]

FATTY ACIDS. Organic acids containing a single carboxyl radical (COOH) and otherwise only carbon and hydrogen; there are many different fatty acids, differing in the number of carbon and hydrogen atoms.

FECES. The material egested from the enteron through the anus.

FEMALE. An individual which produces egg-cells but not sperm-cells.

FERTILITY. Ability to reproduce.

FERTILIZATION. Fusion of two gametes, especially of their nuclei.

FIBRILS. Small fibers or threads within cells.

FIBRO-VASCULAR BUNDLES. Strands of tissue containing woody fibers and tubular vessels, running lengthwise through the stems, roots, and leaf veins of all pteridophytes and spermatophytes.

FILTRABLE VIRUSES. Ultramicroscopic organisms parasitic within the cells of other organisms.

FISSION. Asexual reproduction by division of an organism into two or more equal, or nearly equal, parts.

FLAGELLUM. A protoplasmic process, longer than a cilium, whose movements usually effect locomotion of the cell.

FLORAL ENVELOPES. The calyx and corolla; i.e., the outer whorls of flower parts, not directly concerned in reproduction.

FLOWER. A group of modified leaves of several kinds, including sporophyls, arranged in concentric whorls; a *complete* flower consists of calyx, corolla, stamens, and carpels, but in many flowers some of these are absent.

FOOD. Any material which can either yield energy for the activities of an organism or supply matter for its growth.

FORMED BODIES. Localized differentiated regions or structures within the cytoplasm.

FOSSILS. Remains or traces of dead organisms preserved by natural processes.

FREQUENCY-DISTRIBUTION. The numbers of individuals in the several classes composing a variable population.

FRUIT. A structure formed from the ovary (and sometimes other parts) of a flower, containing the seed.

FUEL SUBSTANCE. A substance which can be oxidized to yield energy in the organism.

FUEL VALUE. The quantity of energy liberated by the oxidation of a substance in the organism; usually expressed in Calories per gram.

FUNGI. Thallophytes without chlorophyl [often used as including also the bacteria].

GALVANOTROPISM. Movement determined by the direction of an external electric current.

GAMETE. A cell which unites with another cell in sexual reproduction.

GAMETOPHYTE. The sexual generation of a plant. (*cf.* SPOROPHYTE.)

GANGLION. A group of nerve cells, especially the cell-bodies.

GASTRIC JUICE. The fluid secreted by the stomach.

GASTRULA. An embryo in the two-layered stage, consisting of ectoderm and endoderm enclosing the enteron.

GASTRULATION. The formation of the gastrula from the blastula.

GEL. A mixture of solid or semi-solid consistency containing a large proportion of liquid entrapped in the meshes of its solid component.

GELATION. The change of a fluid dispersion into a gel.

GENE. A unit hereditary factor, an ultramicroscopic particle (probably a single molecule) capable of self-reproduction and mutation.

GENETIC. Pertaining to the original internal factors depending on the descent of the organism.

GENOTYPE. The genetic constitution of an organism or a group of genetically identical organisms. (*cf.* PHENOTYPE.)

GENUS. A taxonomic group, next above a species.

GEOLOGICAL. Pertaining to the structure and history of the earth.

GEOTROPISM. Movement determined by the direction of gravitational force.

GERM CELLS. Cells capable of reproducing the organism. (*cf.* SOMATIC CELLS.)

GERM PLASM. The germ cells collectively.

GERMINATION. The beginning of growth from a spore or a seed.

GILLS. External respiratory organs of aquatic animals.

GILL-SLITS. A series of paired openings from the sides of the pharynx through the body wall to the exterior, found in all chordates, at least in embryonic stages.

GLAND. A cell or organ specialized for secretion.

GLUCOSE. $C_6H_{12}O_6$, the most common monosaccharide, the chief fuel substance of most organisms.

GLYCEROL. $C_3H_5(OH)_3$, a water-soluble organic compound entering into the synthesis of fats and phospholipins and derived from them by hydrolysis; commonly called *glycerine*.

Glycogen. A complex carbohydrate (polysaccharide), one of the chief stored food substances of most animals, fungi, and bacteria.

Gonads. The essential reproductive organs of multicellular animals, in which the gametes are formed.

Gonia. The germ cells in the period of multiplication preceding the growth period.

Gonoducts. The ducts through which the gametes reach the exterior of the body, found in most animals above the coelenterates.

Green plants. Plants containing chlorophyl.

Growing point. The region at the apex of each filament, stem, or root, to which growth and cell division are largely confined in most plants.

Growth. Increase in size of an organism by assimilation.

Growth period. The period in the development of the germ cells preceding the maturation divisions, during which they increase greatly in size and during which synapsis occurs and the tetrads are formed.

Growth stage. The intermitotic (non-dividing) stage of the cell; often called the *resting stage*.

Guard-cells. A pair of cells surrounding each stoma, whose movements open and close the stoma.

Habit. A usually invariable response determined by the previous experience of the individual; a conditioned reflex.

Habitat. The particular kind of environment inhabited by a particular kind of organism.

Haploid. The number of chromosomes in each gamete; i.e., a single "set" of chromosomes. (*cf.* Diploid.)

Hemoglobin. An iron-containing protein in the blood of many animals, in combination with which oxygen is transported through the body.

Hepatic portal system. A part of the circulatory system, in all vertebrates, by which blood is carried from the stomach and intestine to the liver.

Heredity. The transmission of genes from ancestors to descendants through the germ cells.

Hermaphrodite. A monoecious organism.

Heterotrophic. Requiring organic compounds among the food substances taken into the organism from outside. (*cf.* Autotrophic.)

Heterozygous. Having the two genes of an allelomorphic pair different. (*cf.* Homozygous.)

Holophytic. Obtaining energy from light by photosynthesis.

Holozoic. Obtaining organic food materials by ingestion.

Homolecithal egg. An egg-cell with the yolk uniformly distributed throughout the cytoplasm and usually relatively small in amount.

Homologous chromosomes. The two chromosomes which pair at synapsis.

Homologous organs. Organs having structural and developmental similarities due to genetic relationship. (*cf.* Analogous organs.)

Homozygous. Having the two genes of an allelomorphic pair alike. (*cf.* Heterozygous.)

Hormone. An internal secretion having some specific effect on metabolism, development, or response of the organism or some particular part of it.

Hydration. Chemical combination of water with a substance dissolved in it.

Hydrolysis. Chemical decomposition of a substance by combination with water.

Hypocotyl. The stem of an embryonic seed-plant, below the point of attachment of the cotyledons. (*cf.* Epicotyl.)

Independent assortment. The distribution, at the reduction division, of the genes of different allelomorphic pairs located in different pairs of homologous chromosomes, the distribution of any such pair of allelomorphs being entirely independent of that of any other such pair.

Ingestion. The taking of solid material into a cell or into the enteron.

Inhibition. The stopping of some activity by a stimulus.

Instinct. A usually invariable complex response independent of any previous experience of the individual; a complex unconditioned reflex.

Insulin. An internal secretion of the pancreas essential for the normal metabolism of carbohydrates.

INTELLIGENCE. The ability to learn by experience, i.e., to form conditioned reflexes.
INTERMEDIATE NEURONS. Neurons connecting sensory with motor neurons.
INTERNAL SECRETION. Secretion into the blood. Any substance or mixture thus secreted.
INTESTINE. The chief digestive portion of the enteron in most animals.
INVERTEBRATE. Any animal which is not a vertebrate.
ION. A part of a molecule, consisting of one or more atoms, with an electric charge.
KIDNEYS. The chief excretory organs of vertebrates.
KINETIC ENERGY. Energy inherent in the motion of a body or of its component particles. (*cf.* POTENTIAL ENERGY.)
KINGDOM. A primary taxonomic division; all organisms are usually divided into two kingdoms, plants and animals.
LACTOSE. Milk sugar, a disaccharide found in the milk of all mammals.
LARVA. An active immature animal differing markedly from the adult; e.g., a caterpillar, a tadpole, etc.
LECITHIN. A very common phospholipin, found in many, perhaps all, kinds of cells.
LEUCOCYTES. White blood corpuscles, amoeboid cells of several types, found in all multicellular animals.
LIFE. The characteristic activities of protoplasm, viz., metabolism, liberation of energy as movement, heat, etc., responses to stimuli, growth and reproduction.
LIFE CYCLE. The complete series of forms regularly assumed successively by any particular kind of organism.
LINKAGE. The association in heredity of genes located in the same chromosome.
LIPINS. Organic compounds insoluble in water but soluble in various organic liquids; consisting chiefly of carbon and hydrogen with a small proportion of oxygen and (in some cases) other elements; including fats, phospholipins, sterols, etc.
LIVER. A large glandular organ of vertebrates with numerous functions, including various special metabolic processes, storage, and secretion of the bile.
LOCUS. A particular position in a chromosome, which may be occupied by any gene of a particular allelic series.
LYMPH. A fluid consisting of blood plasma and white blood corpuscles.
LYMPHATIC TISSUE. A kind of connective tissue, found in various parts of the body, in which some of the white blood corpuscles are formed.
LYMPHOCYTES. One kind of white blood corpuscles, formed in the lymphatic tissue.
MACROGAMETE. The larger of the two kinds of gametes, in organisms which have gametes of two sizes.
MACROSCOPIC. Visible with the naked eye.
MACROSPORANGIUM. A sporangium bearing macrospores.
MACROSPORE. The larger of the two kinds of spores (in plants which have spores of two sizes), which develops into a female gametophyte.
MACROSPOROPHYL. A sporophyl bearing macrosporangia.
MALE. An individual which produces sperm-cells but not egg-cells.
MALTOSE. Malt sugar, a disaccharide produced by incomplete hydrolysis of starch.
MARROW. A tissue found in the interior of certain bones, in which red blood corpuscles and some kinds of white blood corpuscles are formed.
MATTER. That which occupies space, has mass (inertia) and weight.
MATURATION DIVISIONS. The two final cell divisions in the formation of the gametes (in animals) or spores, in the course of which the chromosome number is reduced from diploid to haploid.
MEAN. The average value of any measurable characteristic in a population; i.e., the sum of its values in all the individuals, divided by the number of individuals.
MEDULLA. The hindmost portion of the brain, adjoining the spinal cord.
MEDULLARY RAYS. Strands of parenchyma connecting pith and cortex, between the fibro-vascular bundles.
MERISTEM. Embryonic tissue of plants, from which all the other tissues are derived by growth, cell division, and differentiation.
MESENTERY. A thin sheet of tissue connecting the enteron with the body wall.
MESODERM. The cell layer between ectoderm and endoderm in the embryos of all animals above the coelenterates. The tissues derived from this layer.
MESOGLOEA. A thin layer of intercellular material between ectoderm and endoderm in coelenterates.

METABOLISM. The chemical reactions occurring in living cells.

METAMORPHOSIS. Transformation of a larva into the adult form.

METAPHASE. The stage of mitosis at which the chromosomes lie in the equatorial plane of the spindle.

METAZOA. Multicellular animals.

MICROBE. A microscopic organism.

MICROGAMETE. The smaller of the two kinds of gametes, in organisms which have gametes of two sizes.

MICROSCOPIC. Invisible with the naked eye, but visible with the microscope; i.e., between about 0.1μ and 100μ in diameter.

MICROSPORANGIUM. A sporangium bearing microspores.

MICROSPORE. The smaller of the two kinds of spores (in plants which have spores of two sizes), which develops into a male gametophyte.

MICROSPOROPHYL. A sporophyl bearing microsporangia.

MITOSIS. The normal process of cell division in most organisms, involving the longitudinal splitting of each chromosome and the distribution of one half of each chromosome to each daughter cell.

MIXTURE. Any material composed of more than one kind of molecules. (*cf.* SUBSTANCE.)

MODE. The most frequent value of any measurable characteristic in a population.

MODIFICATION. Any variation caused by non-genetic factors.

MOLECULES. The smallest particles into which any substance can be divided without chemical change.

MONOECIOUS. Having the two kinds of gametes produced by the same individual; i.e., not having separate sexes. (*cf.* DIOECIOUS.)

MONOSACCHARIDE. A simple sugar; i.e., a carbohydrate which cannot be decomposed by hydrolysis into simpler carbohydrates.

MORPHOGENESIS. The production of the characteristic form and structure of a cell or an organism.

MOTOR NEURON. A neuron which transmits excitation directly to an effector.

MUCUS. A slimy fluid secreted by gland cells present in many epithelia, called *mucous membranes.*

MUSCLE. A tissue specialized for the production of movement by contraction (i.e., shortening) of its cells. A sheet, bundle, or mass of such tissue.

MUTATION. A change in a gene.

MYELIN SHEATH. A fatty envelope surrounding a nerve fiber.

MYOFIBRILS. Longitudinal fibrils in muscle cells.

MYONEMES. Contractile fibrils in protozoa.

NATURAL SELECTION. The automatic selection of organisms for superior viability and fertility under natural conditions, resulting from the tendency of all organisms to increase in numbers by reproduction and the limitation of this increase by environmental factors.

NEPHRIDIA. Excretory organs found in many invertebrates.

NERVE. A group or bundle of nerve fibers.

NERVE CELL. A cell specialized for the transmission of excitation.

NERVE FIBER. A filamentous cytoplasmic extension of a nerve cell.

NERVE IMPULSE. A state of excitation transmitted along a nerve fiber.

NEUROID TRANSMISSION. The transmission of excitation by cells other than nerve cells.

NEURON. A nerve cell.

NITRIFYING BACTERIA. Bacteria which oxidize ammonia to nitrites, and nitrites to nitrates.

NITROGEN-FIXING BACTERIA. Bacteria which form nitrogen compounds from free nitrogen.

NOTOCHORD. A longitudinal solid rod of cells above the enteron in all chordates, at least in embryonic stages; replaced later, in the vertebrates, by the vertebrae.

NUCLEOLUS. A small rounded body within the nucleus.

NUCLEOPLASM. The protoplasm of the nucleus exclusive of the chromatin; also called *nuclear sap.* [The term *nucleoplasm* is often used to mean all the protoplasm of the nucleus, including the chromatin as well as the nuclear sap.]

NUCLEUS. The portion of a cell containing the chromatin.

NUTRITION. The intake of food substances, their distribution within the organism, metabolism, and elimination of waste products.
OÖCYTES. The auxocytes of the female, which give rise to the egg-cells.
OÖGONIA. The gonia of the female, which give rise to the oöcytes.
ORDER. A taxonomic group, between class and family.
ORGAN. A localized part of an organism, specialized for some particular function.
ORGANIC ACIDS. Organic compounds containing the carboxyl radical (COOH).
ORGANIC BASES. Organic compounds derived from ammonia (NH_3) by the replacement of one or more of its hydrogen atoms by organic radicals.
ORGANIC COMPOUNDS. Compounds of carbon and hydrogen in which some (or, rarely, all) of the hydrogen may be replaced by other elements or radicals.
ORGANISM. An individual living thing—a plant or animal.
OSMOSIS. Diffusion through a semi-permeable membrane.
OVARY. (1) The female gonad of animals, in which the egg-cells are formed. (2) The hollow basal portion of the pistil of seed-plants, in which the ovules are formed.
OVIDUCTS. The female gonoducts.
OVIPAROUS. Laying eggs, either before or shortly after they are fertilized. (*cf.* VIVIPAROUS.)
OVULE. The macrosporangium of seed-plants.
OVUM. The egg-cell.
OXIDATION. Chemical combination of a substance or some of its constituents with oxygen. [In general chemistry the term *oxidation* is used in a much broader sense, including many other reactions analogous to this but not necessarily involving oxygen.]
PANCREAS. The chief digestive gland of vertebrates.
PARASITE. An organism which lives on or in another living organism, from which it derives its nourishment.
PARASYMPATHETIC SYSTEM. That portion of the autonomic nervous system which is connected with the brain and the posterior end of the spinal cord, and whose ganglia lie in or close to the organs they innervate.
PARENCHYMA. A relatively undifferentiated tissue.
PARTHENOGENESIS. Development of an egg-cell without fertilization.
PEDOGENESIS. Reproduction by a larva.
PELLICLE. A thin, flexible external cell membrane, outside the plasma membrane.
PEPSIN. An enzyme secreted by the stomach, which partially hydrolyzes proteins.
PEPTONES. Products of incomplete hydrolysis of proteins.
PERISTALSIS. Rhythmic contractions of the wall of the enteron or other tubular organs, traveling in successive waves in one direction.
PERITONEUM. The membrane lining the coelom.
PETALS. The separate parts of the corolla.
PETIOLE. The stalk of a leaf.
PHAGOCYTOSIS. The ingestion of solid particles by a cell.
PHARYNX. The portion of the enteron immediately behind the mouth cavity.
PHASES. The physically distinct components of any coarse or colloidal mixture.
PHENOTYPE. The visible characteristics of an organism or a group of apparently identical organisms. (*cf.* GENOTYPE.)
PHLOËM. That portion of the fibro-vascular bundles which contains the sieve-tubes, usually the outer portion of the bundles. (*cf.* XYLEM.)
PHOSPHOLIPINS. Lipins containing phosphorus and nitrogen, found in all cells; essential components of protoplasm.
PHOTOSYNTHESIS. The formation of carbohydrates from carbon dioxide and water by the absorption of radiant energy of sunlight by chlorophyl.
PHOTOTROPISM. Movement determined by the direction of incident light.
PHYLOGENY. The line of descent of a group of organisms.
PHYLUM. A taxonomic group, next below a kingdom.
PISTIL. A separate carpel or a group of carpels united to form a single compound organ.
PITH. The parenchyma in the center of a stem or root.
PITUITARY GLAND. A ductless gland on the ventral side of the brain, above the roof

of the mouth, composed of two lobes having different origins and different secretions.

PITUITRIN. The internal secretion of the posterior lobe of the pituitary gland, probably containing at least two distinct hormones.

PLACENTA. An organ of most mammals, by which the embryo is attached to the wall of the uterus and through which osmotic exchanges occur between the blood of the embryo and that of the mother.

PLASMA MEMBRANE. The differentiated surface film of protoplasm, of ultramicroscopic thickness.

PLASTIDS. Cytoplasmic formed bodies in which occur special constructive metabolic processes.

POLAR BODIES. The very small, functionless cells which are produced, with the mature egg-cell, by the maturation divisions of the oöcyte.

POLLEN GRAIN. The microspore of seed-plants.

POLLEN TUBE. The male gametophyte of seed-plants.

POLLINATION. The transfer of pollen grains to the stigma.

POLYEMBRONY. The production of two or more embryos from one, by fission.

POLYSACCHARIDE. A carbohydrate each molecule of which yields, by hydrolysis, many monosaccharide molecules.

PONS. A region on the ventral side of the hind part of the brain, an important intermediate station between the cerebrum and the cerebellum.

POPULATION. Any group of individuals, considered as a whole, especially with reference to numbers and statistics.

PORTAL VEIN. The vein carrying blood from the stomach and intestine to the liver.

POTENTIAL ENERGY. Energy inherent in the position or configuration (relative positions of component parts) of a body. (*cf.* KINETIC ENERGY.)

PROPHASES. The early stages of mitosis, preceding the metaphase.

PROPRIOCEPTORS. Special receptors for internal stimuli due to the positions and movements of the parts of the body.

PROTEINS. Complex organic compounds of C, H, O, N, and often other elements, yielding amino-acids by hydrolysis; essential components of protoplasm.

PROTHALLIUM. The gametophyte of vascular plants.

PROTONEMA. The first stage of the gametophyte in mosses.

PROTON. A particle of positive electricity, one of the ultimate constituents of all matter.

PROTOPLASM. Living matter, a complex mixture of organic and inorganic substances, having a complex microscopic and ultramicroscopic structure and certain characteristic activities; viz., metabolism, liberation of energy as movement, heat, etc., responses to stimuli, growth and reproduction.

PSEUDOPODIA. Temporary projections of the protoplasm of a cell, effecting locomotion of the cell and phagocytosis.

PTYALIN. An enzyme secreted by the salivary glands, which partially hydrolyzes starch.

PUPA. A usually quiescent stage of many insects, between the larval and adult stages.

RADIANT ENERGY. Energy transmitted through "empty" space (i.e., space devoid of matter); including light, X-rays, etc.

RADICAL. A group of atoms which acts as a unit in many chemical reactions.

RADICLE. The root of an embryo plant within the seed.

RECEPTACLE. The base of a flower, to which all the parts of the flower are attached.

RECEPTOR. A structure specialized for the reception of some particular kind of stimulus.

RECESSIVE. A gene whose phenotypic effect is largely or entirely obscured by that of its allelomorph. (*cf.* DOMINANT.)

RECOMBINATION. A new combination of genes brought about by the normal processes of crossing-over, reduction, and fertilization.

RECTUM. The terminal portion of the enteron.

REDUCTION. (1) A chemical reaction in which oxygen is removed from a substance. [In general chemistry, the reverse of oxidation in the broad sense.] (*cf.* OXIDATION.) (2) The change of chromosome number from diploid to haploid by the reduction division.

REDUCTION DIVISION. A division involving the separation of members of a homologous pair of chromosomes—such as occur for each pair during meiosis.

REFLEX ARC. A series of neurons transmitting excitation successively from a receptor through the central nervous system to an effector; comprising one sensory and one motor neuron with or without one or more intermediate neurons.

REFLEX. A usually invariable response to a particular stimulus; a reflex may be simple or complex, unconditioned or conditioned; when not otherwise qualified the term *reflex* usually means a simple unconditioned response, i.e., one involving only a single action and independent of any previous experience of the individual. (*cf.* CONDITIONED REFLEX, HABIT, INSTINCT.)

REFRACTORY STATE. The state of a cell for a brief period immediately following excitation, during which it cannot be excited again by any stimulus.

REPRODUCTION. The production of new cells or organisms from those already living.

RESPIRATION. The intake of oxygen and elimination of carbon dioxide. [Often used as including oxidation in the cells.]

RESPONSE. Any change of activity resulting from a change of external or internal conditions. (*cf.* STIMULUS.)

RESPONSIVENESS. The property of responding to changes of conditions by changes of activity.

RESTING STAGE. The intermitotic or growth stage of the cell.

RHIZOID. A root-like organ of simple structure; distinguished from a true root by not containing fibro-vascular bundles.

ROOT-HAIRS. Filamentous projections of the epidermal cells of roots shortly behind the growing point.

SALIVARY GLANDS. Three pairs of glands located near the mouth, which secrete saliva into the mouth.

SALT. A substance which produces positive ions other than H^+ and negative ions other than OH^-.

SAP. The watery solution of salts, etc., in the ducts and tracheids of a plant.

SAPROPHYTIC. Obtaining organic food substances by absorption from the dead remains or products of other organisms.

SARCOPLASM. The liquid portion of the cytoplasm of a muscle cell, between the myofibrils.

SECRETIN. An internal secretion of the intestine, which stimulates the pancreas to secrete pancreatic juice.

SECRETION. The elimination from cells of substances which have been synthesized or accumulated in these cells. Any substance or mixture thus secreted. [Often used as including also the synthesis of such substances in the cells.]

SEDIMENTARY ROCKS. Rocks formed by the deposition in water of sand, clay, mud, or lime, which subsequently hardens under pressure.

SEED. An embryo sporophyte surrounded by the remains of the mother gametophyte (endosperm) and external integuments derived from the parent sporophyte.

SEGREGATION. The separation of the two genes of an allelomorphic pair into different germ cells at the reduction division.

SELECTION. Any process tending to favor the preservation and reproduction of one type of organism rather than another.

SELF-FERTILIZATION. Union of gametes both derived from the same individual. (*cf.* CROSS-FERTILIZATION.)

SEMI-PERMEABLE MEMBRANE. A membrane through which some, but not all, of the components of a solution can diffuse.

SENSE ORGAN. A multicellular receptor organ, including sensory cells and accessory structures associated with them.

SENSORY CELL. A unicellular receptor.

SENSORY NEURON. A neuron which either acts as a receptor itself or receives excitation directly from a receptor which is not a neuron; its axon usually runs into the central nervous system.

SEPALS. The separate parts of the calyx.

SEPTA. Transverse partitions dividing the coelom into a series of cavities.

SEX-CHROMOSOMES. A particular pair of chromosomes containing genes which (normally) determine the sex of the organism.

Sex-linked genes. Genes in the sex-chromosomes, which are therefore linked in heredity to the genes determining sex.
Sexual reproduction. Reproduction involving the fusion of two cells (gametes), especially of their nuclei.
Sieve-tubes. Tubular structures in the phloëm portion of fibro-vascular bundles, composed of elongate cells whose walls are perforated by fine pores giving direct protoplasmic continuity from cell to cell.
Solute. A substance dissolved in another.
Solution. A mixture in which one or more substances are dispersed in the form of separate molecules or ions throughout another substance.
Solvent. The substance in which another is dissolved.
Soma. The somatic cells collectively.
Somatic cells. Cells incapable of reproducing the organism. (*cf.* Germ cells.)
Species. A taxonomic group, supposed to be a group of individuals which do not differ from each other more than offspring of the same parents may do, and all of which may interbreed freely; in practice, however, the lines between species are often drawn arbitrarily with little or no reference to these criteria.
Spermary. The male gonad, in which the sperm-cells are formed.
Spermatids. Germ cells of the male after the maturation divisions but before assuming the specialized form of the sperm-cells.
Spermatocytes. The auxocytes of the male, which give rise to the spermatids.
Spermatogonia. The gonia of the male, which give rise to the spermatocytes.
Spermatozoön. A sperm cell.
Sperm-cell. A small, usually motile gamete, containing very little cytoplasm and no yolk. (*cf.* Egg-cell.)
Spermiducts. The male gonoducts.
Spinal cord. The central nervous system, exclusive of the brain, of vertebrates.
Spinal nerves. Nerves arising from the spinal cord.
Spindle. A spindle-shaped group of fibers, converging toward opposite ends of the cell, which appears during mitosis.
Sporangium. A hollow structure in which the spores are formed, in pteridophytes and spermatophytes.
Spore. An asexual specialized reproductive cell.
Sporocyte. A cell from which four spores are formed by the two maturation divisions.
Sporophyl. A modified leaf bearing sporangia.
Sporophyte. The asexual generation of a plant which has an alternation of generations. (*cf.* Gametophyte.)
Stamen. A microsporophyl of a flowering plant.
Standard deviation. The usual measure of the variability of a population in respect to any measurable characteristic: the square root of the sum of the squares of the differences between each individual value and the mean value.
Starch. A complex carbohydrate (polysaccharide), the chief stored food substance of most green plants.
Statistical methods. Special mathematical methods for the elucidation of quantitative variations affected by a multiplicity of factors.
Statistics. Certain figures which express the characteristic features of any particular frequency-distribution; e.g., the mean, the standard deviation, etc.
Steapsin. An enzyme secreted by the pancreas, which hydrolyzes fats and some other lipins.
Stereotropism. Movement whose direction is determined by contact with a solid body.
Sterols. Complex lipins, incapable of hydrolysis, found in all cells.
Stigma. A moist, sticky surface at the tip of the pistil, on which the pollen grains germinate.
Stimulus. Any change of external or internal conditions which results in a change in the activities of the organism. (*cf.* Response.)
Stoma. An opening from the intercellular space of a leaf or stem to the outer air, surrounded by two guard-cells.
Style. The elongate portion of a pistil, between the stigma and the ovary, through which the pollen tube grows.

SUBSTANCE. Any material composed of only one kind of molecules. (*cf.* MIXTURE.)
SUBSTRATE. A substance acted on by a catalyst.
SUCROSE. Common sugar, a disaccharide found in many plants, e.g., sugar cane, sugar beets, etc.
SUGAR. Any monosaccharide or disaccharide.
SUSPENSION. A dispersion consisting of solid particles in a liquid medium.
SWARM-SPORE. A zoöspore.
SYMBIOSIS. A mutually beneficial relation between a parasite and its host.
SYMPATHETIC SYSTEM. That portion of the autonomic nervous system which is connected with the anterior and middle regions of the spinal cord, and whose ganglia lie close to the spinal cord or in the abdominal cavity.
SYNAPSE. The point of contact between two neurons.
SYNAPSIS. The intimate conjunction of homologous chomosomes shortly before the maturation divisions.
SYNCYTIUM. A continuous mass of protoplasm with several or many nuclei.
SYNTHESIS. The formation of a more complex substance from simpler ones.
TAXONOMIC. Pertaining to the classification of organisms.
TELOLECITHAL EGG. An egg-cell with abundant yolk concentrated toward the lower side of the cell.
TELOPHASES. The final stages of mitosis, during which the daughter nuclei are formed and the cytoplasm divides.
TESTIS. A spermary.
TETRAD. A group of four chromosomes consisting of a pair of homologous chromosomes each split into two daughter chromosomes, formed after synapsis.
THALAMUS. The part of the brain just behind the cerebrum, an important intermediate station between all other parts of the nervous system and the cerebrum.
THYROID GLAND. A ductless gland located in the throat region, below the pharynx, in all vertebrates.
THYROXIN. A hormone secreted by the thyroid gland.
TISSUE. An aggregate of cells of a particular type, or at most a few types, with more or less intercellular material of a particular type.
TRACHEIDS. Elongate hollow cells (i.e., dead cell-walls without protoplasm), with oblique, perforated end walls, in the xylem portion of fibro-vascular bundles.
TRANSPIRATION. The elimination of water vapor from plants, especially through the stomata.
TRIPLOID. Having three haploid sets of chromosomes.
TROPISM. A movement, of growth, orientation, or locomotion, whose direction is determined by the direction from which the stimulus impinges on the organism.
TRYPSIN. An enzyme secreted by the pancreas, which catalyzes the hydrolysis of proteins.
TUBER. A short, thick, subterranean stem with numerous buds; e.g., a potato.
TURGOR. The swollen, rigid condition of a cell due to absorption of water to the limit of distensibility of the cell wall.
TURGOR MOVEMENTS. Movements effected by local decreases of turgor.
ULTRAMICROBE. An ultramicroscopic organism.
ULTRAMICROSCOPE. A microscope in which light is thrown onto the object from the side, so that particles appear as bright specks against a dark background.
ULTRAMICROSCOPIC. Invisible with the ordinary microscope, but visible with the ultramicroscope; i.e., between about 1 mμ and 100 mμ in diameter.
UNIVALENT. A single member of a pair of homologous chromosomes. (*cf.* BIVALENT.)
UREA. A simple organic compound, $CO(NH_2)_2$, the chief nitrogenous waste product of most animals.
URETERS. The tubes carrying urine from the kidneys to the cloaca or to the urinary bladder.
URETHRA. The tube carrying urine from the bladder to the exterior in mammals.
URIC ACID. A nitrogenous waste product, more complex than urea, and usually formed in much smaller amounts.
URINARY TUBULES. The tubules making up the kidney, which produce the urine.
URINE. The fluid excreted by the kidneys, a solution of various waste products.

Uterus. An enlargement of the lower end of the oviduct, in which the eggs are retained temporarily or in which the embryo develops; in some mammals (e.g., man) there is a single uterus formed by coalescence of the two oviducts.

Vacuole. A droplet of watery fluid within the cytoplasm, bounded by a membrane similar to the plasma membrane.

Vagus nerves. The tenth pair of cranial nerves, composed of parasympathetic fibers innervating most of the internal organs.

Variation. Differences among organisms related by descent.

Vascular plants. Plants having fibro-vascular bundles; i.e., the pteridophytes and spermatophytes.

Vein. A relatively thin-walled, distensible blood vessel, carrying blood from the capillaries back toward the heart. (*cf.* Artery.)

Ventral. Pertaining to the lower side (the front in man).

Ventricle. A very thick-walled chamber of the heart which receives blood from the auricle and pumps it into the arteries.

Vertebrae. The series of short bones making up the spinal column, or backbone, of vertebrates.

Vestigial organ. A degenerate, useless organ.

Viability. Ability to live.

Villi. Small cylindrical projections of the inner surface of the small intestine.

Vitamins. A heterogeneous group of organic food substances required in very small amounts.

Viviparous. Giving birth to fairly well-developed young. (*cf.* Oviparous.)

Warm-blooded animals. Animals whose body temperature is (normally) practically constant and usually higher than that of the environment; including the birds and the mammals.

X-chromosomes. The sex-chromosomes of which there are a pair in the female but only one in the male, in most dioecious dipoid organisms.

Xylem. That portion of the fibro-vascular bundles which contains the ducts and tracheids, usually the inner portion of the bundles, constituting the wood in woody plants. (*cf.* Phloem.)

Y-chromosome. A chromosome in the male, which pairs with the X-chromosome at synapsis, and which often contains few or no genes.

Yolk. Stored food substances in egg-cells.

Zoöspores. Flagellate spores, in many algae.

Zygospore. A thick-walled, resting zygote, in many algae.

Zygote. The cell formed by the union of two gametes in sexual reproduction. The diploid organism which develops from this cell. More usually used in the first sense.

INDEX

Each page number in bold-face type indicates either a main reference or a figure. The scientific names of the taxonomic groups (species, genera, etc.) are in italics.